WSRC-TR-98-00428

Airlift Recirculation Well Final Report - Southern Sector

by
R. M. White
Westinghouse Savannah River Company
Savannah River Site
Aiken, South Carolina 29808

DOE Contract No. **DE-AC09-96SR18500**

WSRC-TR-98-00428
Rev. 0

AIRLIFT RECIRCULATION WELL

FINAL REPORT - SOUTHERN SECTOR (U)

R.M. White

UNCLASSIFIED
DOES NOT CONTAIN
UNCLASSIFIED CONTROLLED
NUCLEAR INFORMATION
ADC &
Reviewing
Official: Dismoore Sheehan
(Name and Title)
Date: 4/21/99

SAFETY • RESPONSIBILITY • SECURITY
SRS
SAVANNAH RIVER SITE

Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

DISCLAIMER

AIRLIFT RECIRCULATION WELL
FINAL REPORT - SOUTHERN SECTOR (U)

R.M. White

Publication Date: March 1999

Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

SAFETY • RESPONSIBILITY • SECURITY
SRS
SAVANNAH RIVER SITE

AIRLIFT RECIRCULATION WELL

FINAL REPORT - SOUTHERN SECTOR

Authentication and Approvals:

R. M. White, Author — Date

J. G. Sonnenberg, Manager, ERTS — Date

Abstract

Chlorinated solvents used in the A/M-Area at the Savannah River Site (SRS) from 1952 - 1982 have contaminated the groundwater under the site. Trichloroethylene (TCE) and perchloroethylene (PCE) have migrated downward through the water table and into an underlying confined aquifer; the Lost Lake aquifer. The various source locations and the complex hydrology and geology underlying the A/M Area have resulted in a complex contaminant plume that is advancing along several fronts. Portions of the plume are migrating towards a natural seepline in the vicinity of Tim's Branch, a tributary of the Savannah River. To comply with the requirements of the current SCDHEC Part B Permit, this plume is being addressed by a multi-phase program under the direction of the Environmental Restoration Division (ERD) at SRS. This report details the first phase of this program, the containment of the portion of the plume greater than 500 ppb (TCE) within the Southern Sector of the A/M Area.

Airlift Recirculation Well technology was selected to intercept the leading edge of the contaminant plume in the Southern Sector of the A/M Area. The Airlift Recirculation Well (ARW) is a new and innovative technology with potential for more cost effective implementation than conventional pump and treat systems. Two Airlift Recirculation Wells have been installed and tested (from Dec. 1996 to March 1999) to establish the feasibility of the technology and to quantify performance parameters needed to locate a line of these wells along the leading edge of the contaminant plume. The wells proved to be very sensitive to proper development, but after this requirement was met, performance was very good.

Key design parameters were established to allow the installation of a row of recirculation wells that will intercept and treat the contaminant plume. The initial in-well stripping efficiency was determined to be approximately 60%. A technology enhancement, the Multi-Stage In-Well Aerator (MIA) was identified and deployed. Initial testing indicates that the MIA can achieve in-well stripping efficiencies of 80-90% and perhaps higher.

The installation of the remaining wells in the treatment system will be completed and placed in service in 1999. Additional applications of this technology are under consideration for the Western Sector of the A/M-Area and at the Miscellaneous Chemical Basin.

Contents

List of Figures

List of Tables

Introduction

Metal finishing operations at the Savannah River Site (SRS) A/M-Area utilized chlorinated solvents for degreasing and cleaning activities from the 1950's to the 1980's. From 1952 to 1982 an estimated 13 million pounds of chlorinated solvents, primarily trichloroethylene (TCE) and perchloroethylene (PCE), were used in the M-Area. Much of this solvent evaporated during use but residual solvent was discharged to a process sewer system. Approximately two million pounds of solvent are estimated to have been released to the M-Area Settling Basin. Another one and one-half million pounds was released to the A-014 outfall.

TCE and PCE were first identified in the local groundwater in 1981. Pump and treat technology was initiated in 1983 and continues today. Hazardous materials in the M-Area Settling Basin have been stabilized and the basin has been capped and closed. The TCE and PCE plumes in the groundwater are in the process of characterization and continue to be monitored. The M-Area RCRA Part B permit allows implementation of innovative technologies for the characterization and treatment of dissolved DNAPL (Dense Non-Aqueous Phase Liquid) plumes and soil contamination in the A/M-Areas.

The groundwater plume has moved downward into a confined aquifer (the Lost Lake aquifer) and is continuing generally southward into the southern part of the A/M-Area (the Southern Sector). The Southern Sector is undeveloped and heavily forested. The Part B Permit Application for the Southern Sector of the A/M Area requires the TCE plume to be hydraulically controlled at the 500 ppb isoconcentration location. Airlift Recirculation Well (ARW) technology was chosen for use in this area because of its technical potential and because it treats the groundwater without bringing it to the surface. This eliminates the need to create and permit an outfall for the treated water discharge, thereby reducing costs and the risk of personnel exposure to listed contaminants. Recirculation wells also improve conditions for natural bioremediation by maintaining or increasing levels of dissolved oxygen in the aquifer.

An areal view of the A/M Area of the Savannah River Site is presented on Figure 1. The A/M Area has been divided into sectors, based roughly upon location relative to the central part of the area. Quarterly monitoring well data and depth discrete soil headspace data from soil borings was used to estimate the location of the leading edge of the 500 ppb isoconcentration contour of the TCE plume. This plume is shown on Figure 1. The configuration of the TCE plume in the Lost Lake aquifer consists of two primary components within the Southern Sector. A larger lobe was estimated to extend along a half-mile front from the vicinity of monitoring well MSB-040 to monitoring well MSB-074. A narrower plume appears to follow Tim's Branch, a tributary of the Upper Three Runs Creek, and a receptor of discharges from the A-014 Outfall.

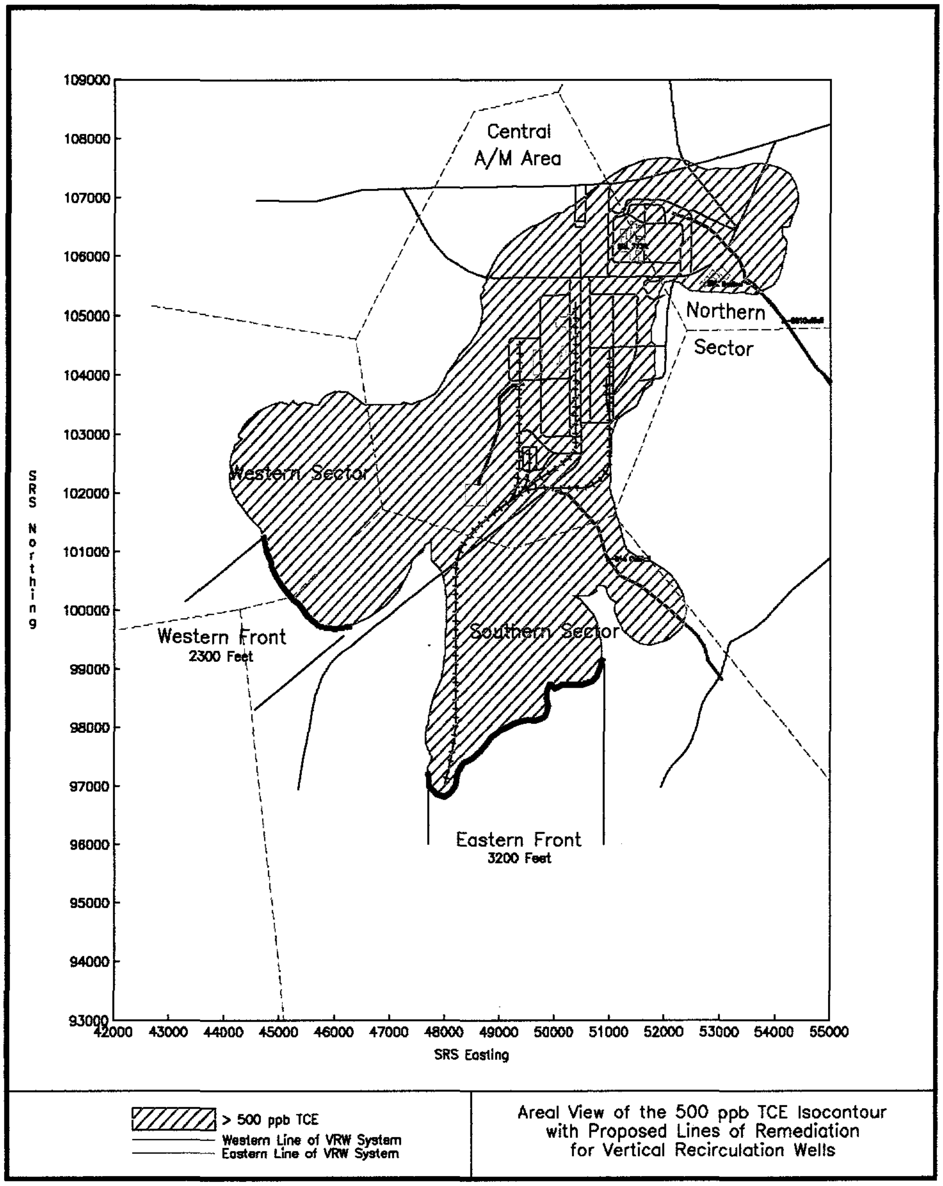

Figure 1: Trichloroethylene plume at 500 ppb

The objective of this study was to install and to test two airlift recirculation wells (one at each end of the broader lobe of the plume; i.e. the Eastern Front) and to determine the following information:

- the size of the area under the hydraulic control of the recirculation well (the Zone of Capture or ZOC);

- the size of the area in which treated water is recaptured for another pass through the recirculation well (the Zone of Recirculation or ZOR);
- the in-well vapor stripping efficiency of the wells;
- the overall treatment efficiency of the wells relative to the contaminated plume;
- the length of time necessary to establish the recirculation well Zone of Capture;
- the feasibility of using recirculation well technology to control the contaminant plume at the 500 ppb isoconcentration line;
- the appropriate well spacing along the Eastern Front for effective plume control;
- operating data necessary for preparation of the revised Corrective Action Engineering Report and associated permits for this area.

The initial results from this work are described in a progress report (Airlift Recirculation Well Test Results – Southern Sector, WSRC-TR-97-00246). Problems with temporary utility services, well development, and higher than expected contaminant levels in the eastern part of the site resulted in the bulk of the effort being directed towards one well, SSR-012.

Conceptual Design

Much of the fundamental research concerning recirculation wells can be traced to the work of Herrling and Stamm in developing the GZB concept. The GZB (Grunwasser Zirkulations Brunnen or groundwater circulation wells) concept is a generalization of the UVB concept. The UVB (Unterdruck Verdampfer Brunnen or vacuum vaporizer wells) concept utilizes a motor driven pump to circulate groundwater and a vacuum system to aerate the water to remove volatile contaminants. See Figure 2.

The Airlift Recirculation Well is, first of all, an in-well vapor stripping system. Additionally, these wells set up a recirculation zone within the aquifer. Air injected near the bottom of the airlift pump (see Figure 3) rises toward the surface creating a column of air and water. The air/water mixture, being lighter than the water in the surrounding saturated zone, is pushed upward. As the air/water mixture passes through the pump, volatile contaminants are stripped from the water and are discharged with the air.

As groundwater is pumped from the bottom of the aquifer and reintroduced at the top of the aquifer a circulating flow of water is created. Depending upon the natural flow patterns present, the recirculating groundwater may pass through the well a number of times before slipping downgradient.

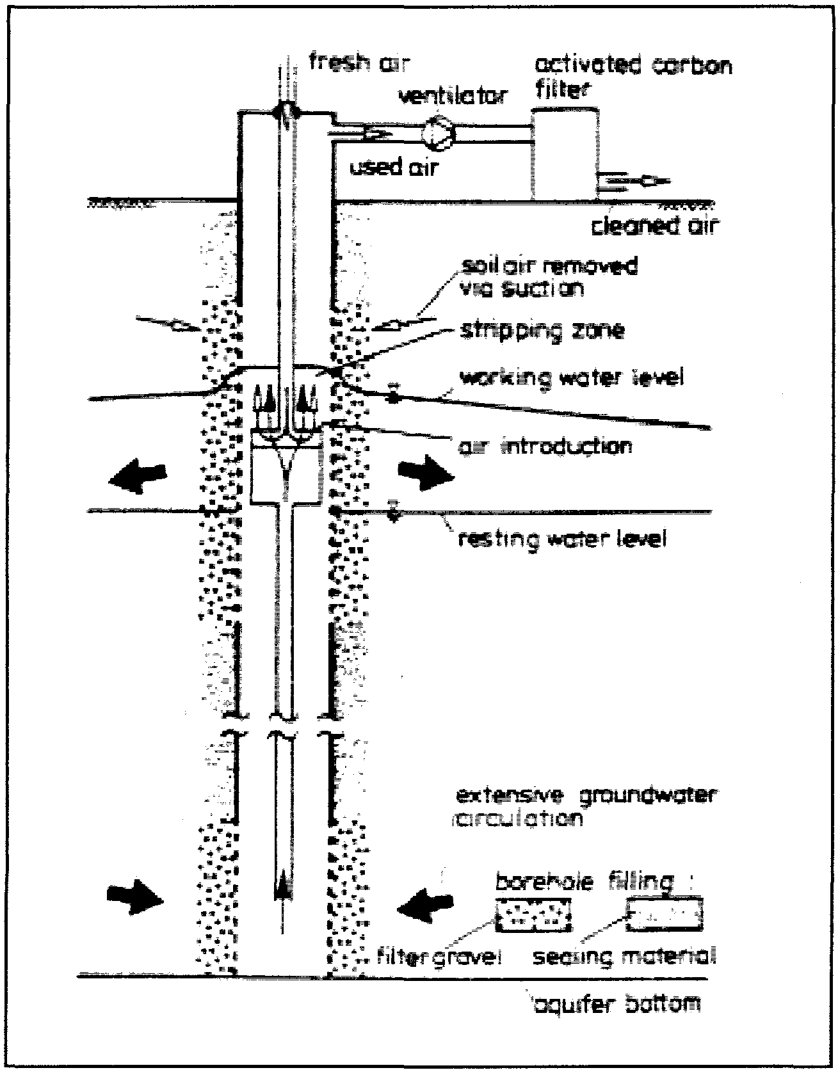

Figure 2: UVB concept

Early UVB research led to the development of various distinct systems for in-well vapor stripping. In the United States, the ARW concept was developed by Gorelick & Gvirtzman (the NoVOC's concept) and by Pennington (the Density Driven Convection concept). The ARW utilizes airlift pumping and direct air injection for the in-well pumping and stripping actions rather than vacuum and a pinhole plate as is used in the UVB. All of these technologies, however, are intended to create the same recirculating flow of groundwater in the aquifer. Consequently, Herrling's original analysis of groundwater flow and recirculation cell development is still applicable.

Our first two well locations were selected to be just downgradient of the projected 500 ppb isoconcentration contour at each end of the Eastern Front. This established the two ends of a proposed line of recirculation wells intended to capture and treat this plume front.

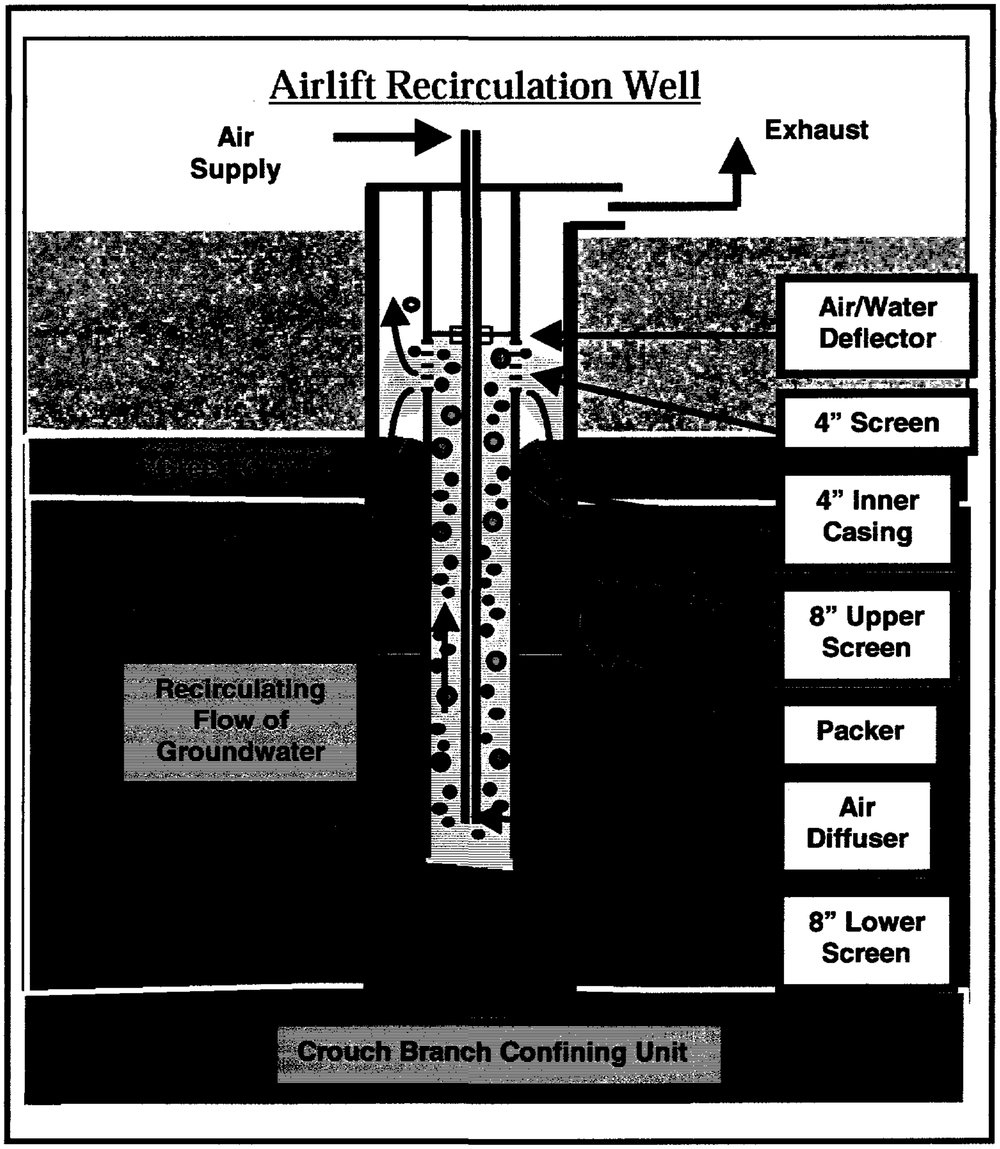

Figure 3: Recirculation well operation

Herrling's approach was used to estimate the number of recirculation wells required to capture the plume front at various pumping rates. For a flow range of 5 – 80 gpm, the number of wells required was estimated to be from 5 – 13. Twelve was felt to be a conservative number, however rather than committing immediately to a fixed number of wells, two initial sites were chosen; one at each end of the Eastern Front. This would allow the ARW concept to be tested to confirm the proper well spacing necessary before committing the resources needed for a full suite of wells. Twelve wells would result in a uniform well spacing of 252 feet. The first two wells were designated SSR-001 and SSR-012. These two wells were completed near the end of 1996.

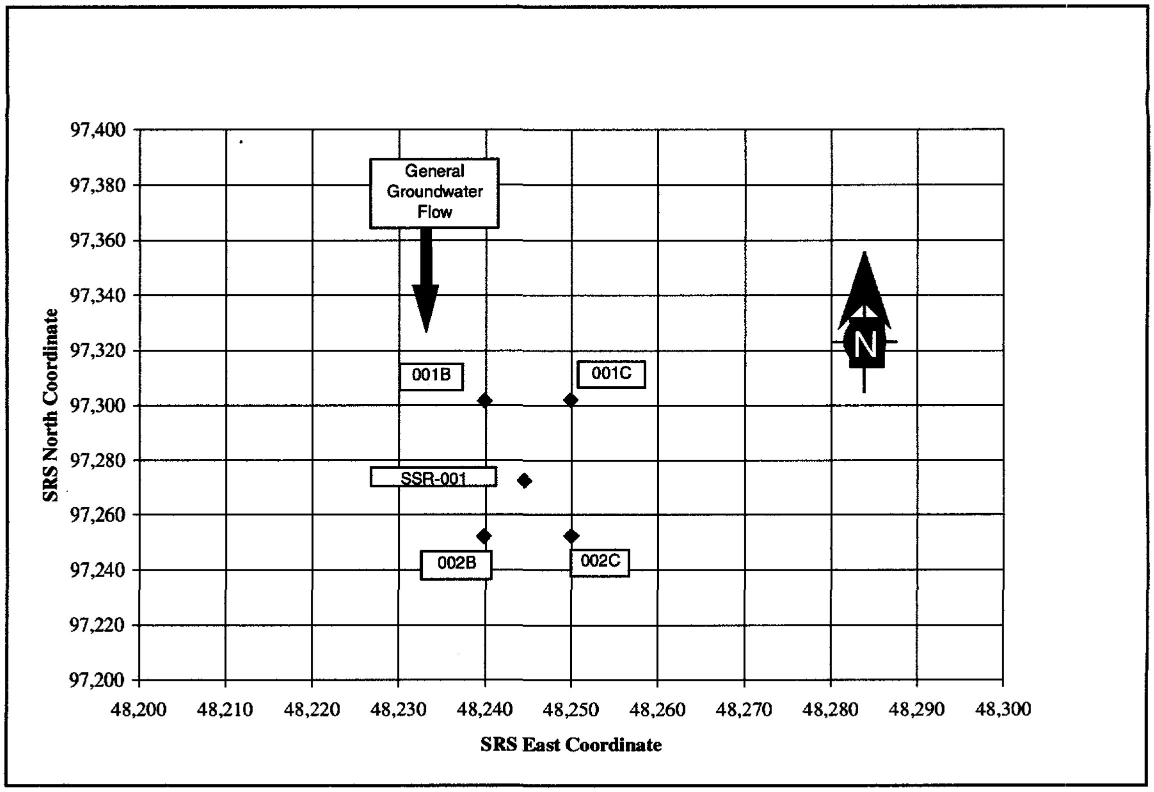

Figure 4: SSR-001 Piezometer locations

A piezometer cluster was located upgradient and downgradient of each recirculation well for observing groundwater levels and for groundwater sampling. Each cluster consisted of one 2 inch PVC casing screened in the top of the Lost Lake aquifer (the "C" well) and one 2 inch PVC casing screened in the bottom of the Lost Lake aquifer (the "B" well). The piezometers were spaced on 10 feet lateral centers. The upgradient piezometer cluster at well SSR-001 was located 30 feet from the recirculation well and the downgradient piezometer cluster was located 20 feet from the recirculation well (reference Figure 4).

The piezometer clusters at well SSR-012 were spaced equally, 20 feet upgradient and 20 feet downgradient (reference Figure 5). The different upgradient spacing was simply to provide an additional point of reference for the data. In July 1997 three well clusters (SSM-005, SSM-006, and SSM-007) were added to the east of SSR-012. These wells were spaced to provide a uniformly spaced series of wells lateral to the natural groundwater flow for use in quantifying the Zone of Capture. In December 1997 two additional well clusters (SSM-008 and SSM-009) were added between SSR-011 and SSR-012. These wells were added to better evaluate the combined effect of running two adjacent recirculation wells.

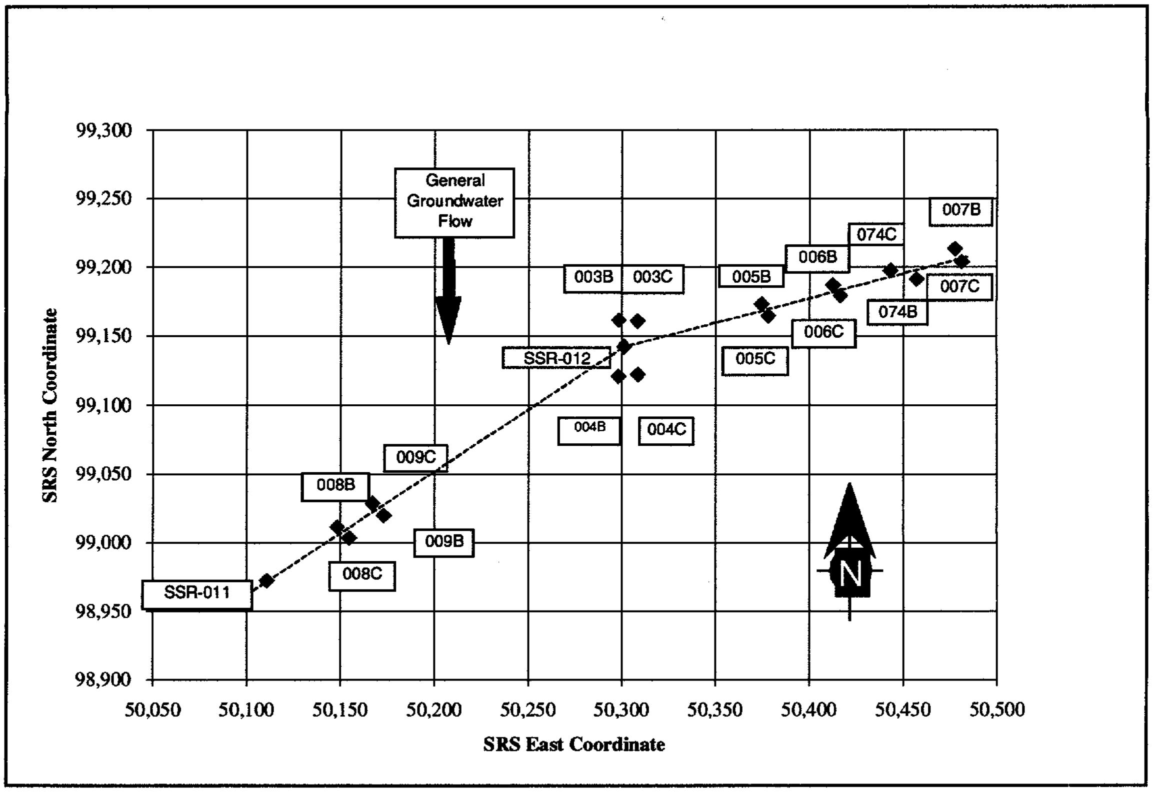

Figure 5: SSR-012 piezometer locations

The recirculation well consists of an 8 inch schedule 80 PVC well casing with two separate ten foot long screen zones; one at the top of the aquifer and one at the bottom of the aquifer (reference Figure 6). The PVC screens have 0.020 inch machined slots on a 1/8 inch spacing. The casing was grouted in place with gravel pack at each screen and a bentonite seal between the screens. An airlift pump was constructed from 4 inch schedule 40 PVC well casing and a 1 inch schedule 80 PVC airline. The 4 inch casing was installed inside the 8 inch casing with an inflatable packer to isolate the annulus between the two 8 inch screen zones. The bottom of the 4 inch casing (pump inlet) was placed just above the 8 inch screen at the bottom of the aquifer. A five foot long screen was placed in the 4 inch casing such that the bottom of the screen was eight feet above the potentiometric head in the top of the aquifer. This is the airlift pump outlet. The 1 inch air line was installed in the 4 inch well casing with a discharge diffuser located seven feet above the bottom of the 4 inch casing. The air diffuser was fabricated by drilling 76 - 5/32 inch diameter holes in a 12 inch long piece of 1 inch schedule 80 PVC pipe. The intent was to create relatively small bubbles discharging laterally while minimizing backpressure on the air line and the risk of plugging the diffuser with dirt, bacterial growth, etc.

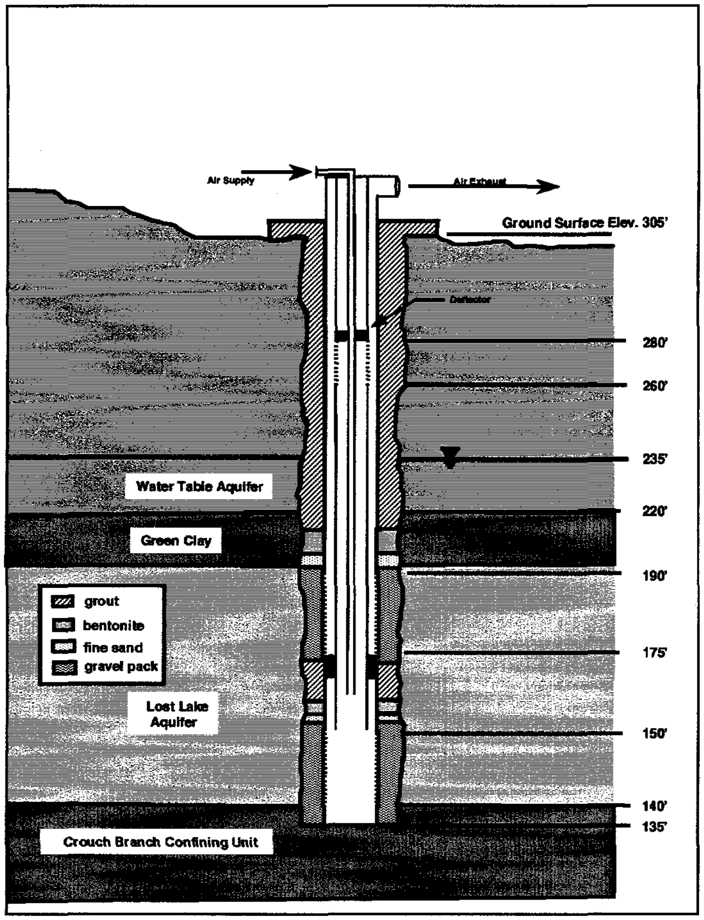

Figure 6: Recirculation well installation

A duplex, oil-free air compressor package was installed at each recirculation well to provide compressed air. The compressor package was rated at 110 cfm at 125 psi. Because of the remote location of the recirculation wells, initially there were no utilities available. To expedite testing of the wells, portable generators were installed at each well site. The installation of permanent power was completed in December 1997.

Typical aquifer properties are listed in Table 1. Aquifer thickness, grain size, soil type, and porosity were derived from drill cuttings, core analysis and borehole logs from the recirculation wells and from earlier borings in the vicinity. Measurements from the upper and lower observation wells during pump tests allowed the calculation of hydraulic conductivity. The anisotropic ratio is simply the ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity. The potentiometric gradient was measured at the observation wells and was used with the conductivity, aquifer thickness and porosity to calculate pore velocity. Transmissivity is the product of horizontal hydraulic conductivity and aquifer thickness.

Table 1: Southern Sector Aquifer Parameters

Parameter	Value
Aquifer thickness	54 ft.
Grain size	V. fine to v. coarse sand, predominantly fine to medium
Sediment type	sub-mature quartz sand
Porosity	0.15 - 0.25
Horizontal hydraulic conductivity	25.8 ft/day
Vertical hydraulic conductivity	1.43 ft/day
Anisotropic ratio	18
Horizontal pore velocity	0.19 ft/day
Transmissivity	1393 ft^2/day

Grundfos sample pumps were used to take water samples from the observation wells for analysis. Water samples were analyzed for TCE and PCE concentrations using a gas chromatograph with a headspace analyzer (EPA SW-846 method 8260A). Results are included in the Appendix (Figures 24 – 43 and Tables 4 – 8). Dissolved oxygen (D.O.) and specific conductivity measurements were made with a YSI analyzer.

Gas samples were taken from the air supply line and from the exhaust stack at each recirculation well and analyzed for TCE and PCE concentrations by direct injection into a gas chromatograph (EPA SW-846 method 5021). Results are tabulated in Table 9 in the Appendix.

Results and Discussion

Well Development

Initial results demonstrated the sensitivity of the recirculation well technology to proper well development. Special efforts must be made to aggressively develop both the upper and lower screens zones independently. In our case the wells were installed with conventional mud rotary drilling techniques as this is the most practical method at SRS. We were not able to achieve effective well operation until all residual drilling mud and loose fines were removed from both screen zones. This was successfully accomplished at SSR-012 using airlift and pump and swab techniques. However to date, we have not realized the full potential of SSR-001. This information is covered in detail in the earlier progress report (Airlift Recirculation Well Test Results – Southern Sector, WSRC-TR-97-00246). The use of innovative development techniques are being planned to resolve this situation. Alternative well drilling methods that do not rely on drilling muds will be considered for future wells. This report will focus upon results achieved at SSR-012.

Since the functionality of the recirculation well depends in large part upon the amount of water that can pass through the well, a major concern is the susceptibility of the upper screen to plugging with clays and fines from the pumped water. To gauge this we performed a flow test in August 1998, and compared the results with those from a similar test in May 1997. This test involved operating the well at a high flow rate with a level transducer located in the annular space above the upper 8 inch screen. The air supply to the well is shut off and the change in the water level in the annulus is recorded. This provides a direct measurement of the water flow out of the upper screen. As can be seen in Figure 7, although the flow rate had declined marginally, a significantly higher head was required to maintain this flow. This indicates that the upper

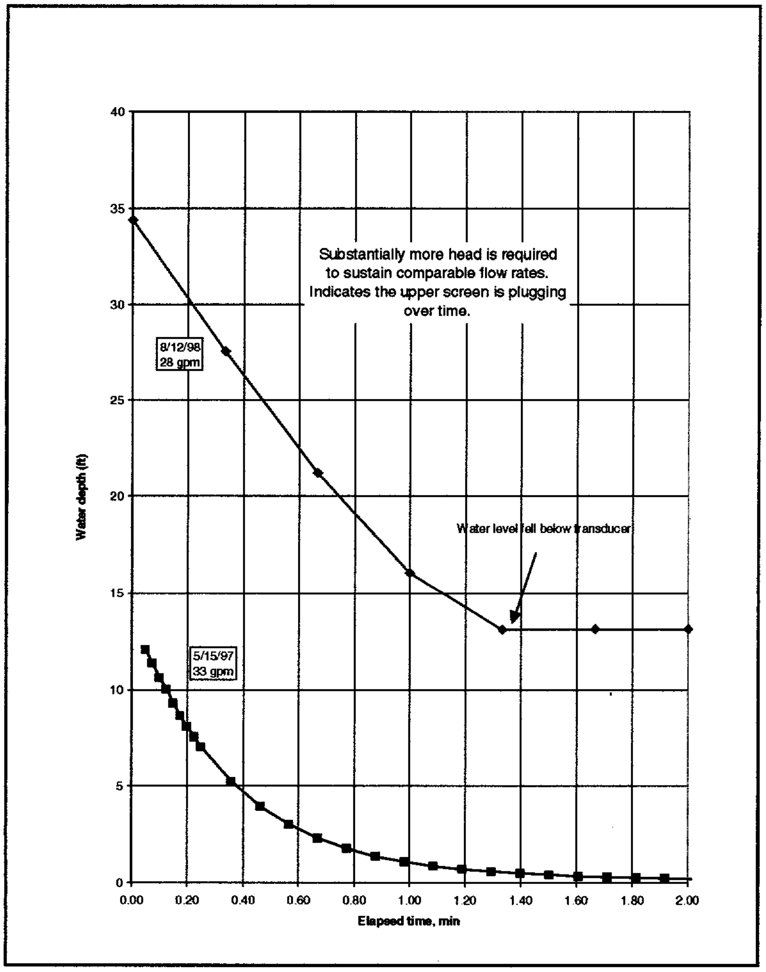

Figure 7: Water flow tests at SSR-012

screen is plugging over time and as should be expected with any injection well, it eventually will need to be redeveloped. The rate of plugging does not appear to be a significant obstacle to long term operation.

After SSR-012 was redeveloped in April 1997, the 4 inch screen was raised 25 feet to allow additional head capacity above the upper screen zone to compensate for partial plugging over time. The 4 inch screen in all new wells will be located approximately 30 feet above the static potentiometric head.

Initial Groundwater Quality

Prior to placing the wells in service, a baseline of water quality in the piezometer clusters was established. Referring to Figure 25, the TCE concentration around well SSR-001 was about as expected; approximately 400 ppb in the bottom of the aquifer and approximately 15-20 ppb at the top of the aquifer. However at the observation wells around well SSR-012, TCE was found in excess of 10,000 ppb in the bottom of the aquifer and approximately 3,000 ppb at the top of the aquifer (refer to Figure 27). The contaminant plume appears to extend much farther down gradient in the vicinity of SSR-012 than expected. Although this may lead to the redefinition of the overall plume treatment strategy at this site, it provided an excellent opportunity to evaluate recirculation well technology in a regime of higher contaminant concentrations.

Dissolved oxygen was found to be near saturation levels at the bottom of the aquifer (see Figure 37) but at relatively low levels at the top of the aquifer.

Zone of Capture

The Zone of Capture is that part of the aquifer from which groundwater is drawn into a well while it is pumping. In designing a treatment system to capture a contaminant plume, the wells must be spaced such that the Zones of Capture overlap to some degree. This helps to insure that the entire contaminant plume is captured. Initially, the proper well spacing was estimated from Herrling's model. Two methods were used to corroborate the original estimate.

First, drawdown measurements were made at the lateral wells to quantify the aquifer response to the operation of the recirculation well. Water level measurements taken at the lateral wells (SSM-005, 006, 007, and MSB-074) are shown in Figure 8. The drawdown levels taken while SSR-012 was in operation indicate that the hydraulic effect of the well extends at least to MSB-074, approximately 160 feet lateral to the natural groundwater flow. From this data a simple particle tracking model was generated to predict the groundwater flow path and travel times from MSB-074 to SSR-012 (see Figure 9 and Table 2). The specific methodology is explained in detail in the initial report. Figure 8 illustrates that the hydraulic gradients created by the recirculation well are much stronger than the existing regional gradient.

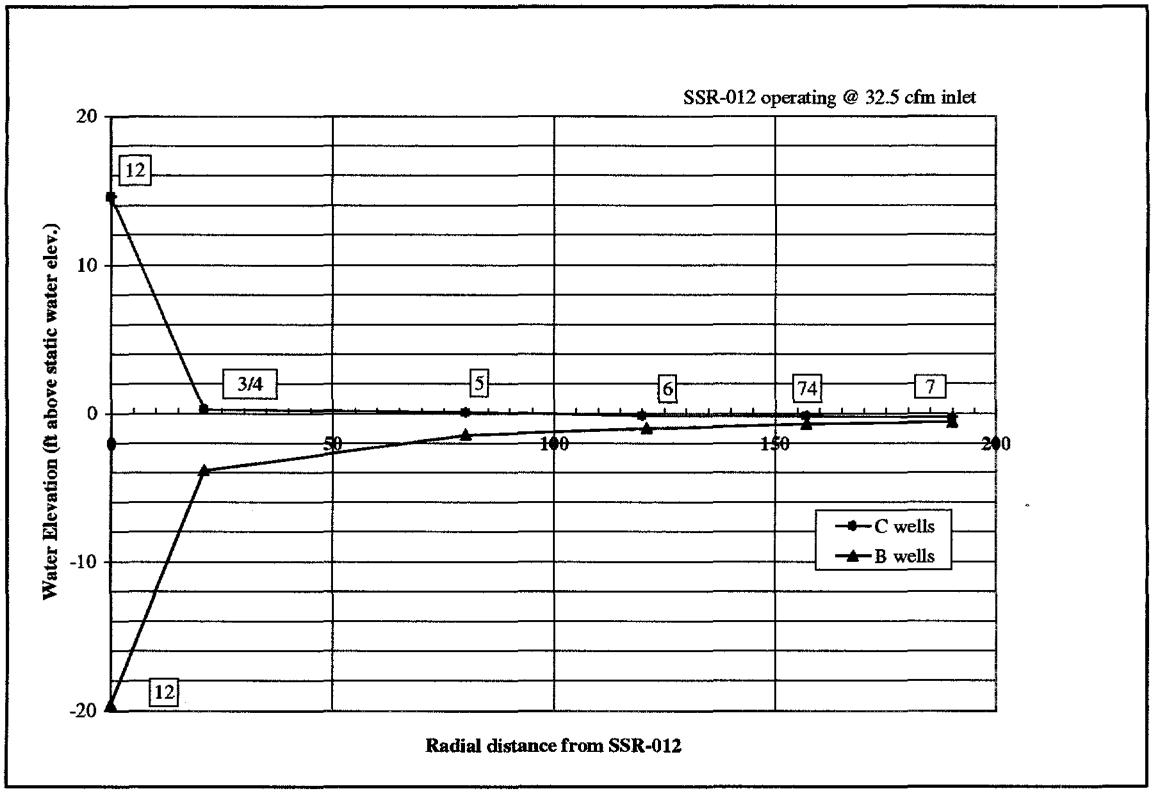

Figure 8: Potentiometric heads at lateral piezometers

As further corroboration, a tracer test was initiated on Feb. 6, 1998. Sodium bromide was introduced into MSB-074B at a concentration of 2,700 mg/L at a controlled rate of 1.1 L/min over an 8 hour period. Samples were taken periodically at the observation wells between MSB-074 and SSR-012 and analyzed for bromide content. The results are shown in Figures 10 – 14 in the Appendix. Figure 9 shows a very strong indication of bromide at well SSM-006B on the 41st day. Table 2 lists the travel times predicted by the model and the actual times of the tracer peaks for comparison.

Table 2: Tracer Results

Well	SSM-006B	SSM-005B	SSM-004B	SSM-003C	SSM-004C
Predicted peak (days)	40	80	110	111	111
Actual peak (days)	41	68	134	143	157

This is a positive indication that the bromide tracer followed the predicted path and was in fact under the hydraulic influence of the recirculation well. The bromide peaks downgradient are quite a bit weaker, indicating that the tracer had diffused or migrated slightly southward, nevertheless, the peaks occur at times reasonably close to what was predicted. This supports the conclusion that recirculation well SSR-012 has established a Zone of Capture of approximately 300 feet in diameter and our initial well spacing of 252 feet is reasonable.

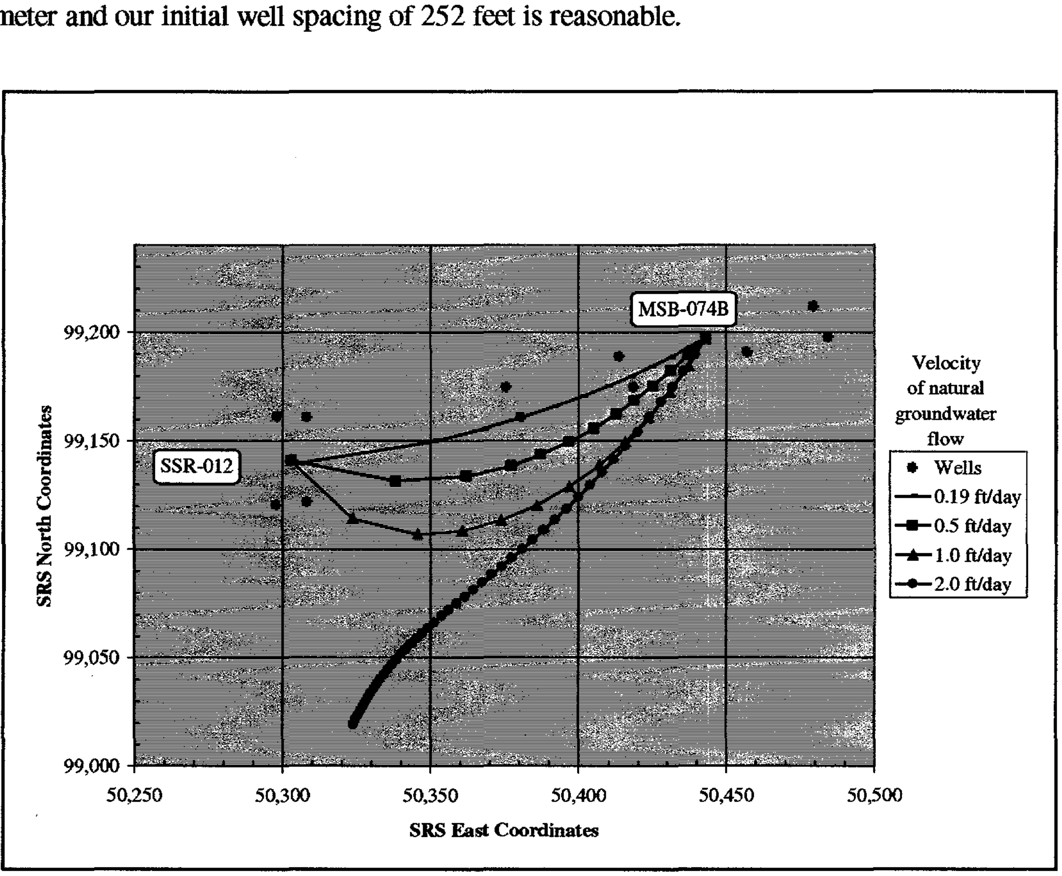

Figure 9: Simulated groundwater flow patterns

Zone of Recirculation

As water is drawn into the lower screen of the recirculation well and discharged back into the aquifer from the upper screen, a three-dimensional hydraulic gradient is created around the well. Because of the anisotropic ratio, K_h/K_v (horizontal hydraulic conductivity / vertical hydraulic conductivity), the bulk of the discharge from the well flows radially outward, taking the path of least resistance. A smaller component of the flow is drawn downward and back into the well where it is again exposed to the stripping effect of the airlift pump. Herrling's model provides a theoretical mechanism to predict the relative size of the recirculated component of the well discharge, but a practical analysis of this ratio is beyond the scope of this report. The portion of the aquifer around the well in which this recirculating flow is significant is referred to as the Zone of Recirculation.

The physical dimensions of the Zone of Recirculation remain the subject of a certain amount of conjecture. The size of the ZOR is dependent upon the anisotropic ratio, the thickness of the aquifer, the length of the upper and lower screen zones, and the magnitude of the natural groundwater flow. Although Herrling's data provide a theoretical means to estimate the size and shape of the zone, we have no cost effective means of proving it. Herrling's model predicts that the

ZOR will be nearly circular in cross-section, extending a distance of 137 feet up and downgradient and 132 feet on either side of the recirculation well, lateral to the natural flow of groundwater. Thus, with the 252 foot well spacing in the Southern Sector, the ZOR should extend completely from one well to the next.

In 1999, work is planned to model the flow patterns around SSR-012 on a finer scale. This is an opportunity to corroborate some of Herrling's results and is intended to provide additional insight into localized flow patterns and the ZOR.

Test Configuration

The recirculation well was equipped with variable orifice flowmeters (rotameters) on the inlet airline and in the exhaust stack. Thermometers and pressure gauges were installed in both air streams. In order to measure the water pumping rate, the well annulus (the area between the 8 inch well casing and the 4 inch airlift pump casing) was "calibrated" to establish a relationship between inlet airflow and water level. This was simply a stepwise tabulation of measured values. A similar relationship was then established between the water level in the annulus and the water flow out of the upper 8 inch screen. To do this a water level transducer was placed in the annulus below the static water level. The airflow was then turned on at a high flow rate (approximately 50 cfm). After conditions stabilized (approximately 10 minutes) the airflow was shut off and the decline in water level was recorded at very short time intervals using a data logger. The cross-sectional area of the annulus is constant, thus the decline in water level over incremental periods of time can be converted into a flow rate. The two relationships were plotted against their common parameter (water level) to create a nomograph that allows pumping rate to be approximated from inlet airflow. This nomograph is attached as Figure15. Typical operating parameters at SSR-012 are shown in Table 3.

Table 3: Typical Operating Parameters at SSR-012

Date	Inlet Air Flow	Est. Water Pumping Rate	Exhaust Air Flow	TCE Conc. in Exhaust Air	Stripping Efficiency
June, 1998	33 cfm	43 gpm	48 cfm	62.8 ppmv	63 %

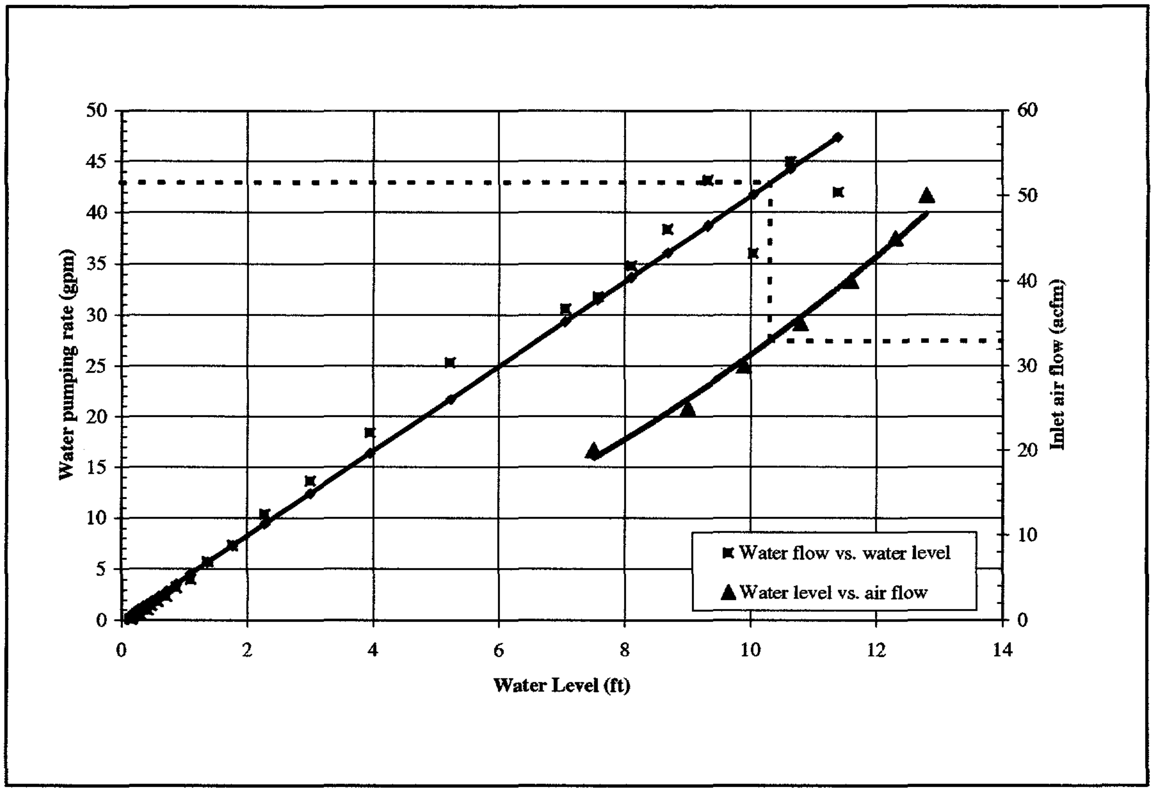

Figure 15: Pumping rate nomograph

Stripping Efficiency

Stripping efficiency is of interest because it provides a metric for comparing the effectiveness of the technology. Stripping efficiency is simply the percentage reduction in the contaminant level of the groundwater as measured at the inlet and outlet of the recirculation well. The stripping efficiency was evaluated by establishing a mass balance around the recirculation well. During the redevelopment of SSR-012 in April 1997, the lower screen zone was thoroughly pumped at 48 gpm. A number of water samples were taken which established a background TCE concentration of 4500 ppb at the bottom of the aquifer. Note that this water is a mixture drawn from the entire Zone of Capture.

A simple mass balance for TCE yields:

$$Qao\ Cao + Qwo\ Cwo = Qai\ Cai + Qwi\ Cwi$$

where:

Qao = air flow rate from exhaust stack

Qai = air flow rate into the well

Qwo = groundwater flow out of the upper screen

Qwi = groundwater flow into the lower screen

Cao = concentration of TCE in exhaust air

Cai = concentration of TCE in air supply

Cwo = concentration of TCE in the groundwater discharging into the upper screen zone

Cwi = concentration of TCE in the groundwater at the inlet to the airlift pump.

If we neglect evaporation,

$$\text{Qwi} \cong \text{Qwo}$$

Periodic testing of the inlet air has confirmed that,

$$\text{Cai} \cong 0$$

Substituting and rearranging,

$$\text{Qwo Cwo} = \text{Qwo Cwi} - \text{Qao Cao}$$

Substituting values from Table 3 and converting to common units yields:

Qwo Cwi = 43 gal/min X 4,500 lb. TCE/10^9 lb. H_2O X 8.34 lb. / gal

= 0.0016 lb. TCE / min.

Qao Cao = 48 ft^3 air / min X 62.8 ft^3 TCE / 10^6 ft^3 air X

131.5 g TCE / 24.5 L TCE X 28.3 L / ft^3 X 1 lb. / 454 g

= 0.0010 lb. TCE / min.

Qwo Cwo = (0.0016 - 0.0010) lb. TCE / min.

= 0.0006 lb. TCE / min.

Cwo = 0.0006 lb. X 10^9 / min / (43 gal/min X 8.34 lb./gal)

= 1673 ppb.

Defining single pass stripping efficiency (ηs) as:

$$\eta s = (Cwi - Cwo) / Cwi$$

$$= (4{,}500 - 1{,}673) / 4{,}500$$

$$= 62.8\%.$$

Historically, the single pass stripping efficiency at SSR-012 has been in the 40 – 70% range with the original configuration. While this does not account for supplemental mass removal resulting from the recirculation of the treated water, the first pass stripping efficiency is a significant quantifiable measure of the performance of the ARW. In an attempt to improve the stripping efficiency, new technologies were solicited that could be adapted to the original configuration.

Multi-Stage In-Well Aerator

In September, 1998 the airlift pump was removed from SSR-012 and replaced with a Multi-Stage In-Well Aerator (MIA) designed by Davis Environmental.

This technology also utilizes airlift pumping, but as shown in Figure 14, incorporates additional spargers in the upper and lower screen zones. Thus it utilizes three stages of stripping. The technology has been successfully applied at the University of California – Davis. Initial testing of this configuration at SSR-012 has produced single pass stripping rates of 80-90%. Although the results are very promising, additional testing is needed to confirm these results.

Overall Treatment Efficiency

As can be seen from the attached Tables and Charts, recirculation well SSR-012 has performed very well. Figure 17 illustrates the contaminant mass removed from the aquifer by the recirculation well. Figure 18 illustrates the decline in contamination levels at the lateral wells during the course of the demonstration. Referring back to Figure 1, some of this reduction may be due to the hydraulic control of the plume itself. As the plume is pulled towards the recirculation well, cleaner water from the east is drawn in and displaces the more heavily contaminated water. This again is evidence that the recirculation well technology has established hydraulic control over the edge of the plume.

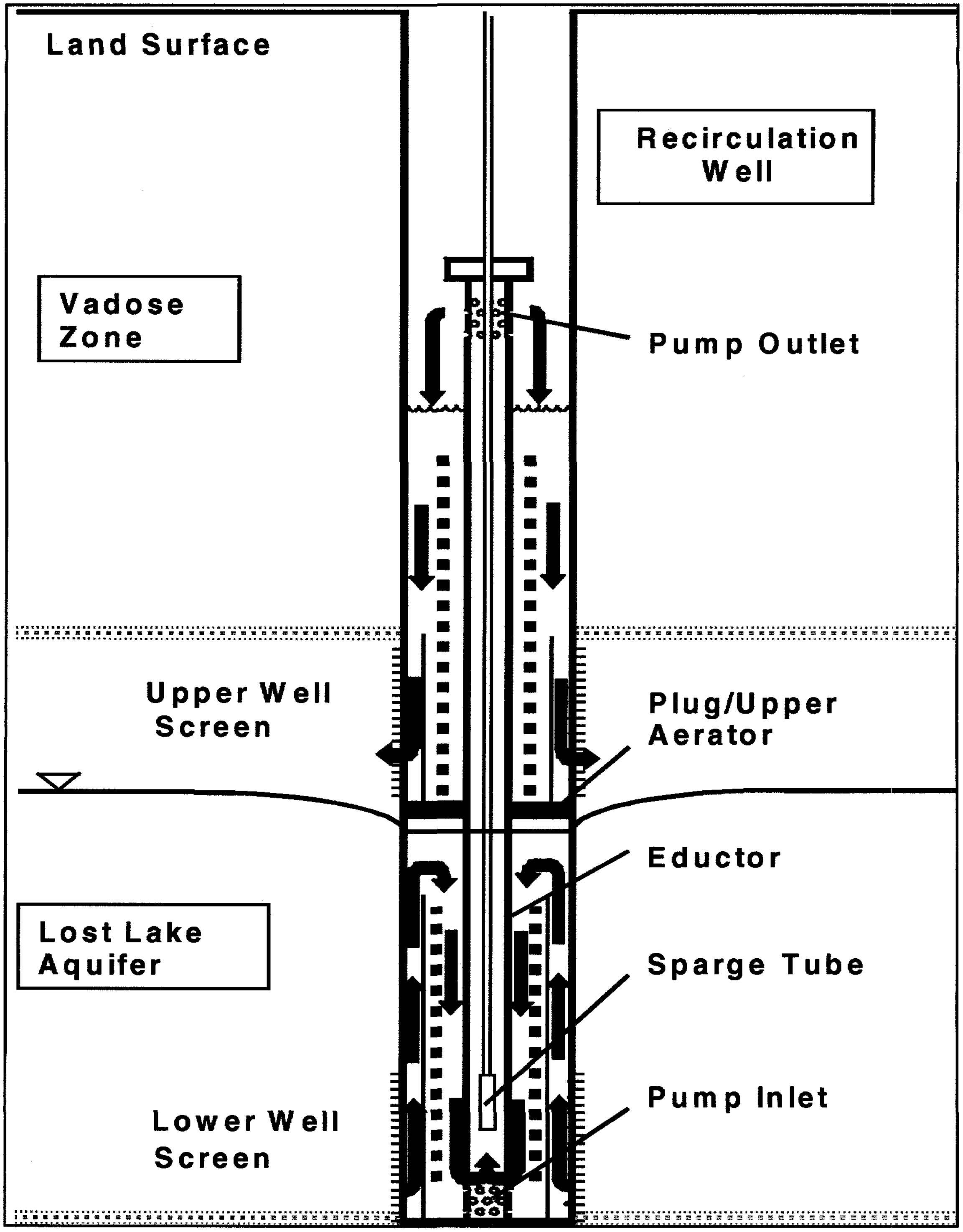

Figure 16: Multi-stage In-well Aerator

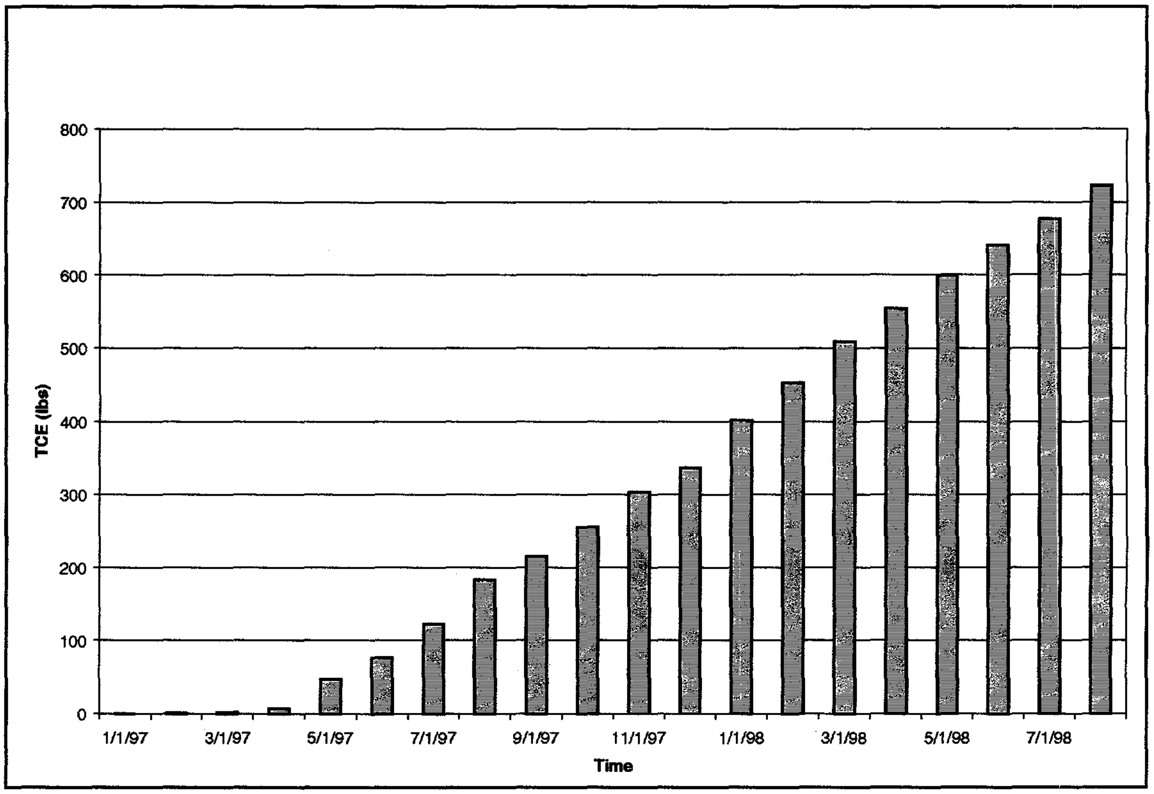

Figure 17: TCE mass removed at SSR-012

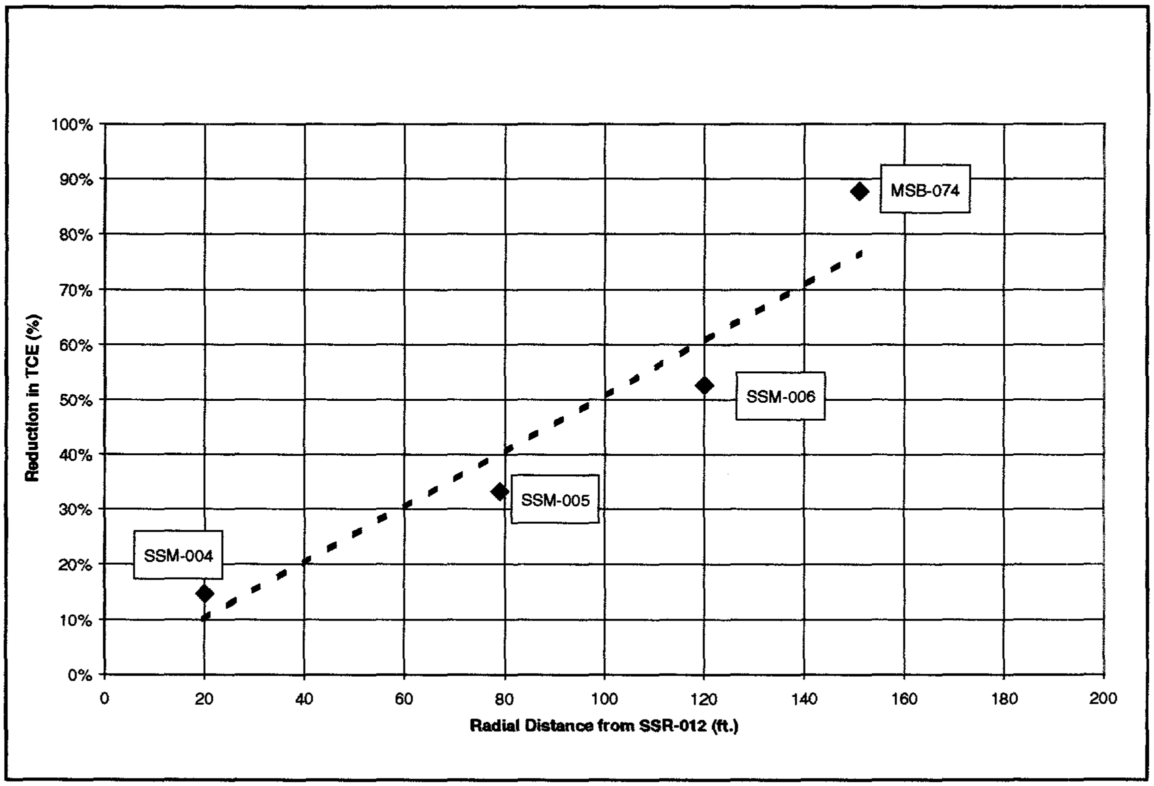

Figure 18:TCE reduction at nearby wells

Much of the effectiveness of the ARW technology hinges upon two factors; the first pass stripping efficiency and the number of passes that a typical water particle makes through the well as it passes through the Zone of Capture. We can determine the first factor relatively easily, as demonstrated earlier. The second factor is much more elusive and lends itself to diverse academic discussion. A simplistic evaluation is presented below.

If we assume that the recirculation cell functions as a continuous flow stirred-tank reactor (CFSTR), a very simple model can be created to predict downgradient contaminant concentrations over time. Although the underlying assumptions; complete mixing within the cell, uniform flows, etc., might be expected to contrast sharply with real conditions, the model does provide a simple comparative metric for the purpose of conceptual discussion. The model schematic is presented in Figure 19.

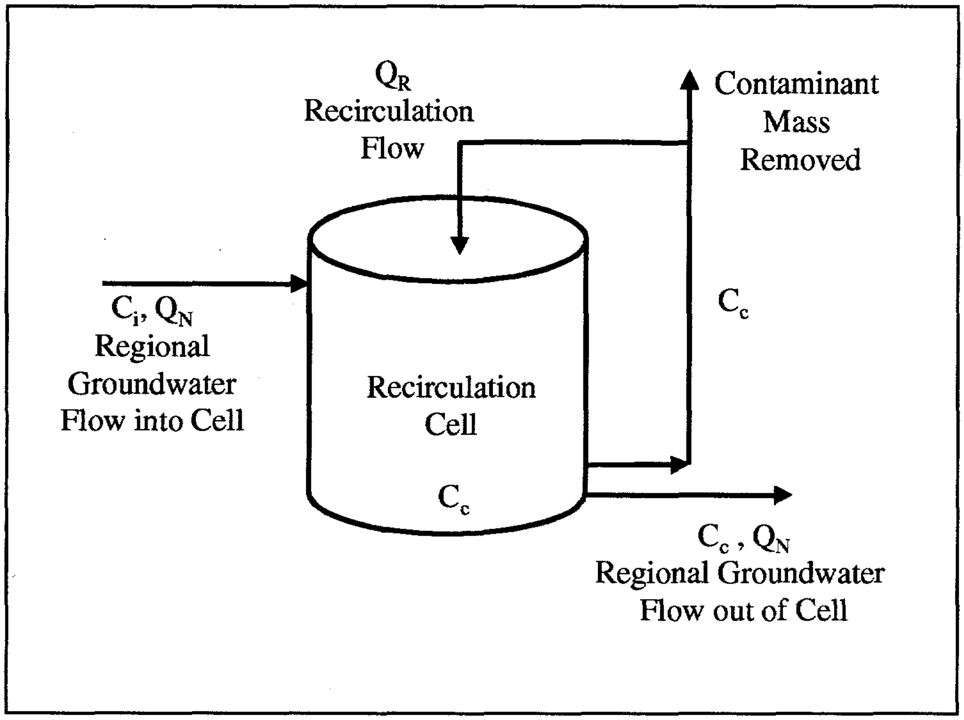

Figure 19: CFSTR model schematic

TCE mass flow into the recirculation cell = TCE mass flow out of the recirculation cell

TCE mass flow into the recirculation cell = Q_N Ci $+ Q_R$ C_C $(1-\eta s)$

where,

Q_N = the regional groundwater flow into the cell,

C_I = the TCE concentration in the groundwater upgradient of the well

Q_R = the recirculation well water pumping rate,

C_C = the contaminant concentration within the recirculation cell, and

ηs = the first pass stripping efficiency.

Q_N can be approximated by,

Q_N = v B D p

where

v = the regional groundwater velocity

B = the aquifer thickness

D = the width of the recirculation cell, and

p = the porosity of the aquifer.

Substituting values,

Q_N = (0.19 ft/day) (54 ft) (252 ft) (0.2) (7.48 gal/cu.ft.) (1 day/1440 min)

= 2.7 gpm.

TCE mass flow out of the recirculation cell = Q_N Cc + Q_R C_C.

The initial conditions were assumed to be:

C_i = 10,000 ppb TCE

Q_R = 43 gpm

C_C = 4,500 ppb TCE.

A spreadsheet model was used to calculate the concentration of TCE in the discharge from the recirculation well over a one year period at stripping efficiencies of 50%, 65%, and 100%. As can be seen in Figure 20, the TCE level was reduced to less than 1,500 ppb within one year and the concentration was continuing to decline although at a declining rate. Given the simplifying assumptions used in this exercise, we would expect the actual results to differ somewhat, but the general trend should be similar. More sophisticated modeling techniques are planned for the future to allow more realistic forecasts.

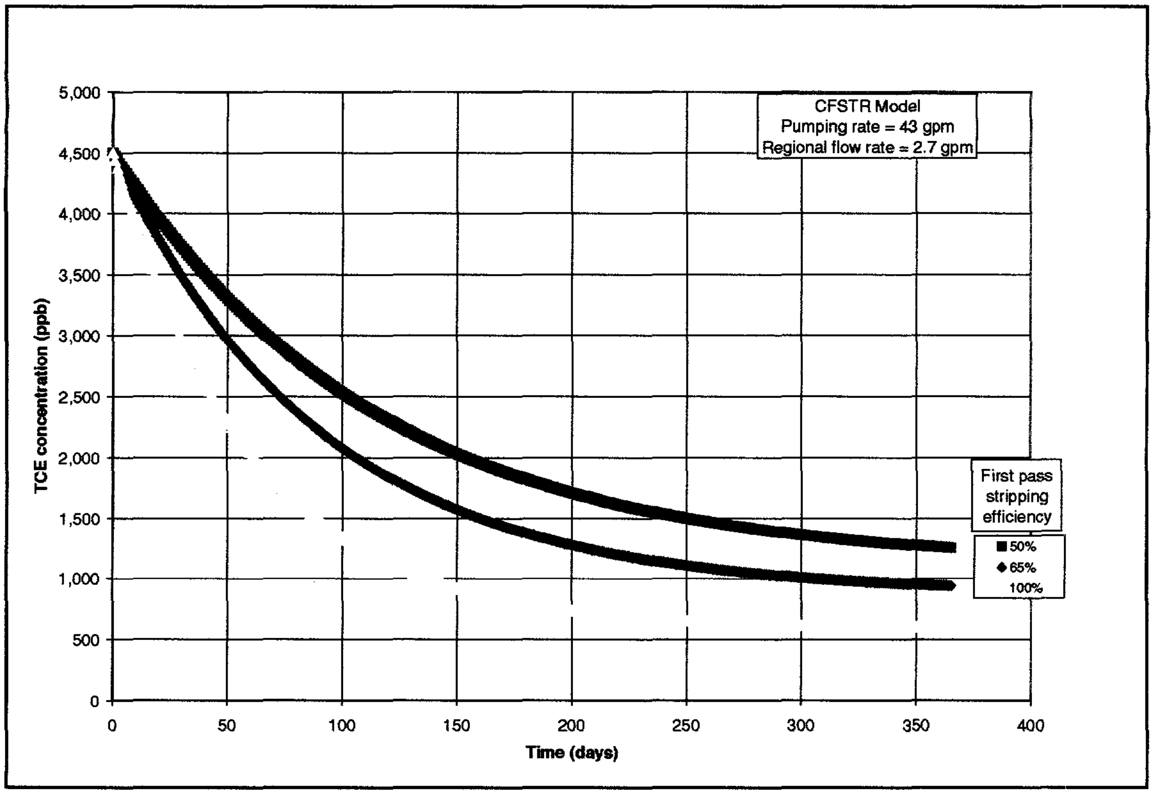

Figure 20: Results of CFSTR model

Time to Establish a Recirculation Cell

Early in the testing, pressure transducers were installed in MSB-074 B & C to measure the aquifer response as SSR-012 was started up. The results are shown in Figure 21. One of the objectives of this project was to determine the time to establish a recirculation cell and how quickly the cell would degrade after the recirculation well was shut down. This information was to provide an idea of how long components could be out of service due to breakdown or for routine maintenance without adversely effecting the treatment objectives of the system. Figure 21 shows that the gradient controlling the recirculating flow of water is established within minutes of placing the well in service. The time required for a water particle to travel from the outer edge of the Zone of Capture to the recirculation well is approximately 140 days as demonstrated in the tracer experiment. The gradient at the top of the aquifer is not as large as the gradient at the bottom of the aquifer so the flow outward will not be as fast.

This is evident from the dissolved oxygen data presented in Figures 34-43. The low naturally occurring D.O. levels at the top of the aquifer create an environment where the dissolved oxygen serves as an effective tracer. Note that after SSR-012 was placed in service, the D.O. levels in the surrounding "C" wells began to rise. We might consider the point at which the D.O. level in each "C" well reached the same level as that of the corresponding "B" well as an indication that the recirculation cell had reached equilibrium. By this measure, the recirculation cell grew to a radius of 120 feet (at SSM-006) over a period of 265 days (Figure 39). Judging by the tracer test results and the D.O. results a complete round trip for a water particle may take between 300 and 500 days.

At startup of the recirculation well the actual recirculation cell gradients are formed within minutes (Figure 21). The recirculation cell then becomes a dynamic mixing zone and may require years to establish steady state conditions. The cell will likewise degrade very quickly if the wells are removed from service; within hours. The aquifer will then return to its natural gradient. The groundwater at the southernmost boundary of the recirculation cell will flow out of the Zone of Capture at the natural flow velocity of 0.19 feet/day. The contaminant concentration of this water will be much lower than the untreated upgradient water, conceivably at less than 100 ppb. Given the low regional flow gradient, short periods of downtime (a few days at the most) for equipment maintenance should not result in gross lapses in groundwater remediation.

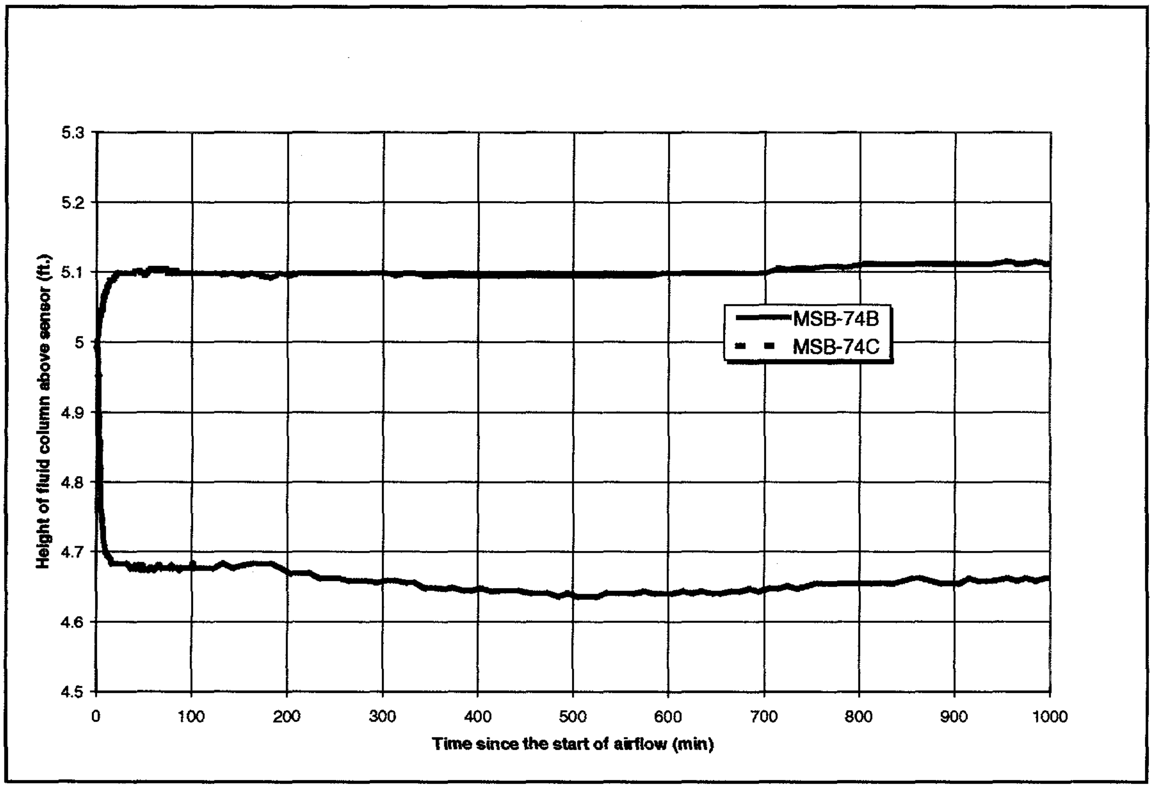

Figure 21: Aquifer response at MSB-074

Conclusions

The test results obtained over the past two years have confirmed the viability of the vertical recirculation well technology in this particular application. The success of the technology has been dependent upon the particular hydrostratigraphy of the Lost Lake aquifer. The relatively coarse sandy aquifer, with little clay/silt stratification, bounded on the top and bottom by clay rich confining layers with an anisotropic ratio of 18 seem to be key parameters for success. The results are consistent with model developed by Herrling, et. al.

Figure 17 illustrates the cumulative contaminant mass that has been removed from the aquifer since it was placed in service. The system has proved to be very reliable and has consistently removed over 1 lb. of TCE per day.

Figures 22 and 23 illustrate the shifts evident in the 8,000 ppb TCE isocontour in the vicinity of SSR-012. Each isocontour was created from the sampling data from the surrounding wells in the month indicated. The 8,000 ppb isocontour was presented because data in the 6,000 to 8,000 ppb range appears regularly and is easily tracked. Other isocontours could have been shown, but this one seemed representative of the general trends. These curves are crude approximations based upon sampling data and although the exact shape of each curve is subject to individual interpretation, as a whole they provide strong evidence that while SSR-012 was in service, the TCE plume was being successfully remediated.

Figure 22: 8,000 ppb TCE isocontours near SSR-012 with the well in service

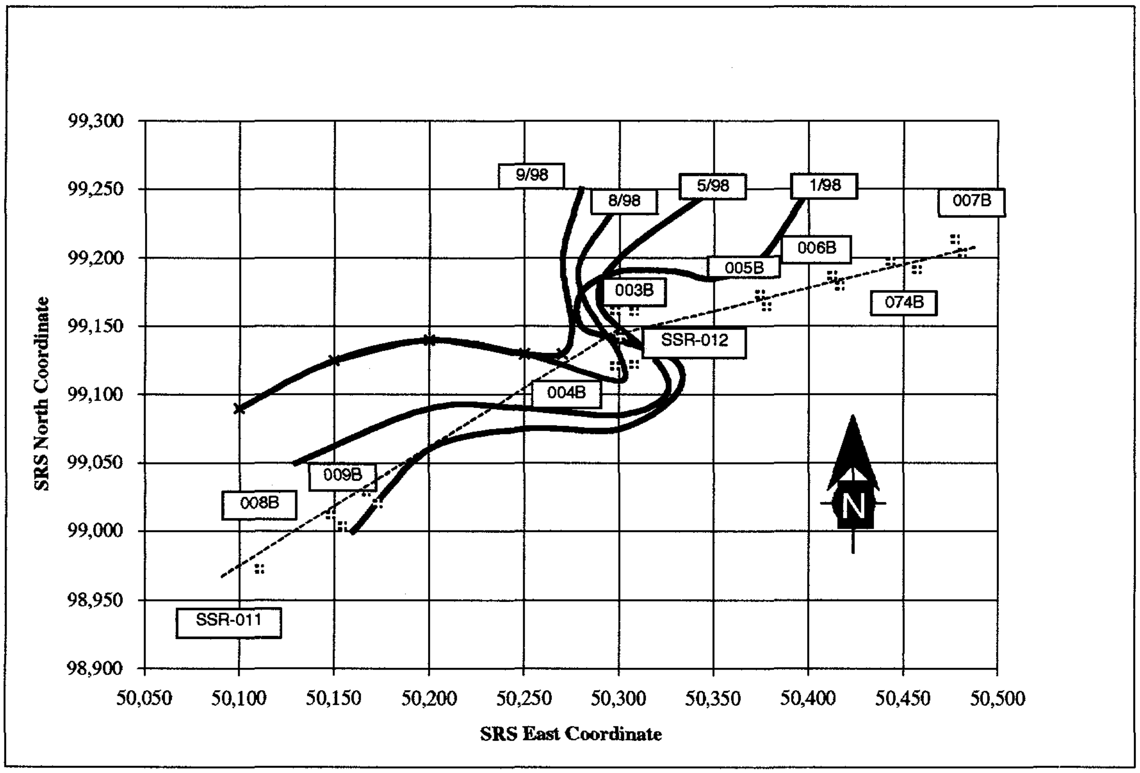

Figure 22 illustrates the effect of the recirculation well on the TCE concentration in the aquifer while the well was operating. Note that as contaminant mass is being removed from the groundwater (as demonstrated in Figure 17), the regional TCE concentration is falling. As discussed earlier, the recirculation well was removed from service in September 1998, to allow the installation and testing of the Multi-Stage In-Well Aerator. After the initial tests with the MIA configuration, the well remained out of service while utility and component upgrades were completed in the area. Figure 23 illustrates the return of higher contamination levels while the well was out of service, corroborating the benefits of the ARW technology.

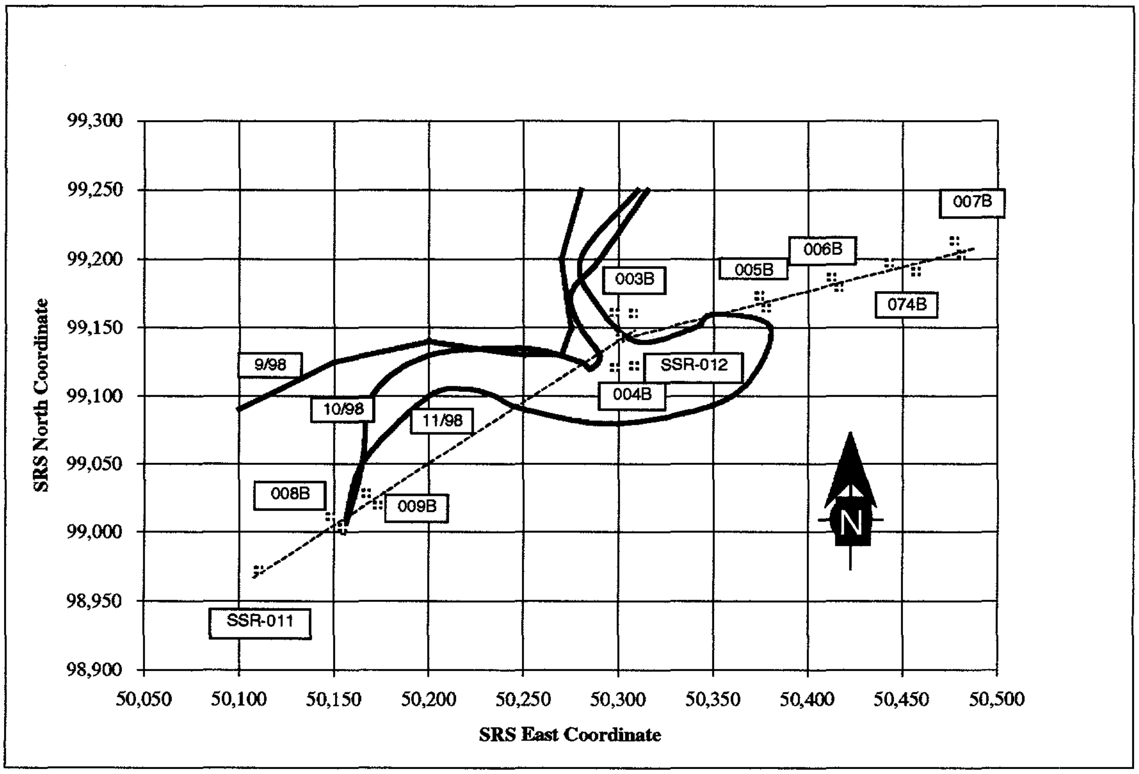

Figure 23: 8,000 ppb TCE isocontours near SSR-012 after the well was shut down

As with many endeavors, as we have gathered information and operating experience with the technology, new questions have arisen. Because of the significant promise of improved efficiencies offered by the MIA technology, it is recommended that further testing be completed to corroborate the initial results. Additionally, the location of piezometers between SSR-011 and SSR-012 offers an excellent opportunity to study the overlap of the Zones of Capture and Recirculation. The resulting knowledge will prove valuable as we pursue additional applications for the ARW technology.

References

Looney, Brian B. and Phifer, Mark A., 1994, A/M Area Groundwater Corrective Action Southern Sector Remediation Technology Alternatives Evaluation, WSRC-RP-94-607.

Herrling, B., and Stamm, J., 1991, Numerical results of calculated 3D vertical circulation flows around wells with two screen sections for in situ on on-site remediation, Proc. IX International Conference on Computational Methods in Water Resources, Denver, CO.

Alesi, E.J., Brinnel, P., Herrling, B., Hirschberger, F., Sick, M.R. and Stamm, J., 1991, In Situ groundwater remediation of strippable contaminants by vacuum vaporizer wells (UVB): operation of the well and report about cleaned industrial sites, Third Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Dallas, TX.

Jackson, Dennis G. and Looney, Brian B., 1996, Development of a Vertical Recirculation Well System for the A/M Area of the Savannah River, WSRC-RP-96-477.

Hiergesell, R.A. and Nichols, R.L., 1997, Estimation of vertical hydraulic conductivity of the Lost Lake Aquifer near recirculation well SSR-012, SRT-EST-97-433.

Hiergesell, R.A. and White, R.M., 1997, Airlift Recirculation Well Test Results – Southern Sector, WSRC-TR-97-00246SRT-EST-97-433.

Stagner, Joe, 1998, Multi-Stage In-Well Aerator Performance Test Results – Well SSR-012.

Appendix

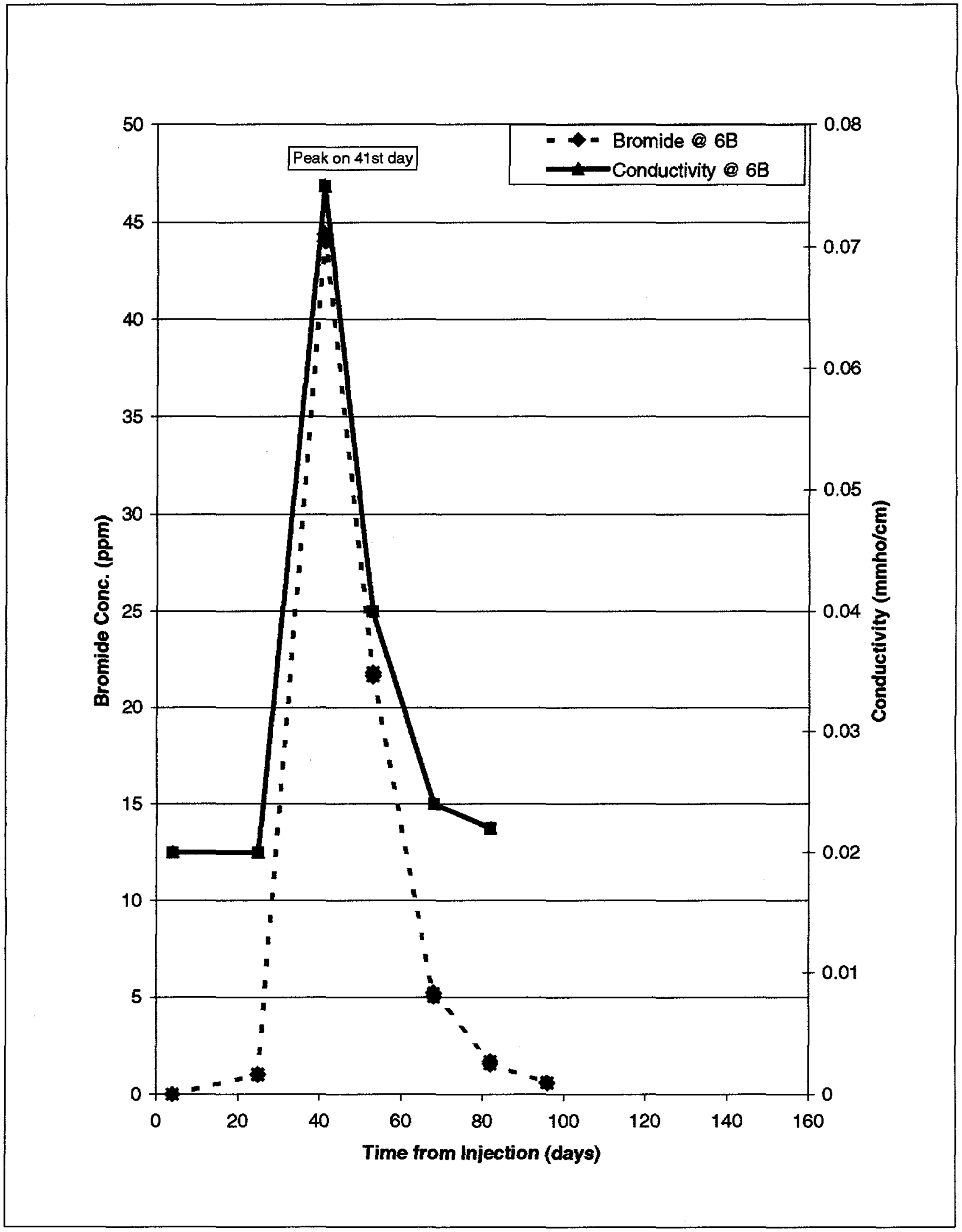

Figure 10: Bromide tracer concentration at SSM-006B

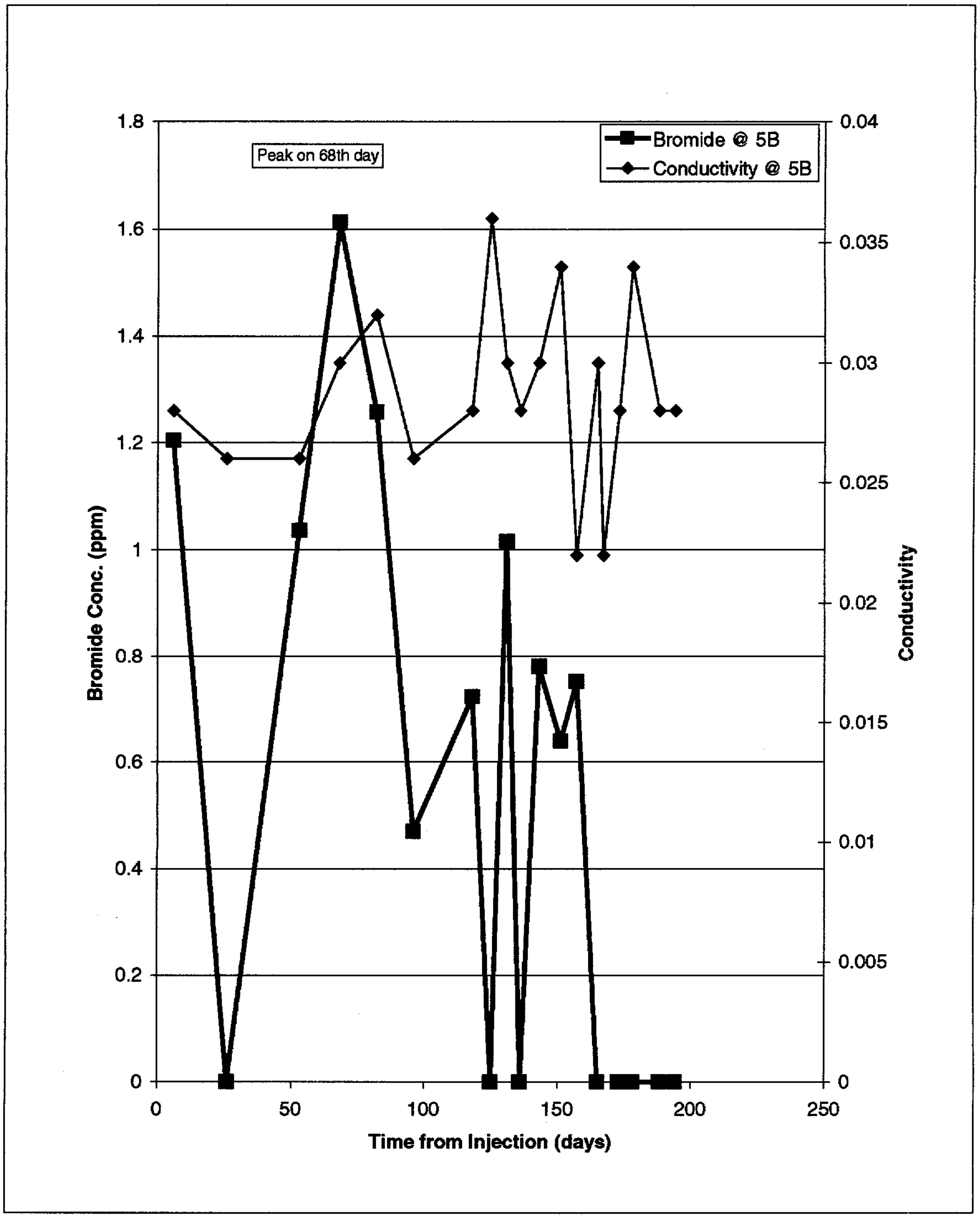

Figure 11: Bromide tracer concentration at SSM-005B

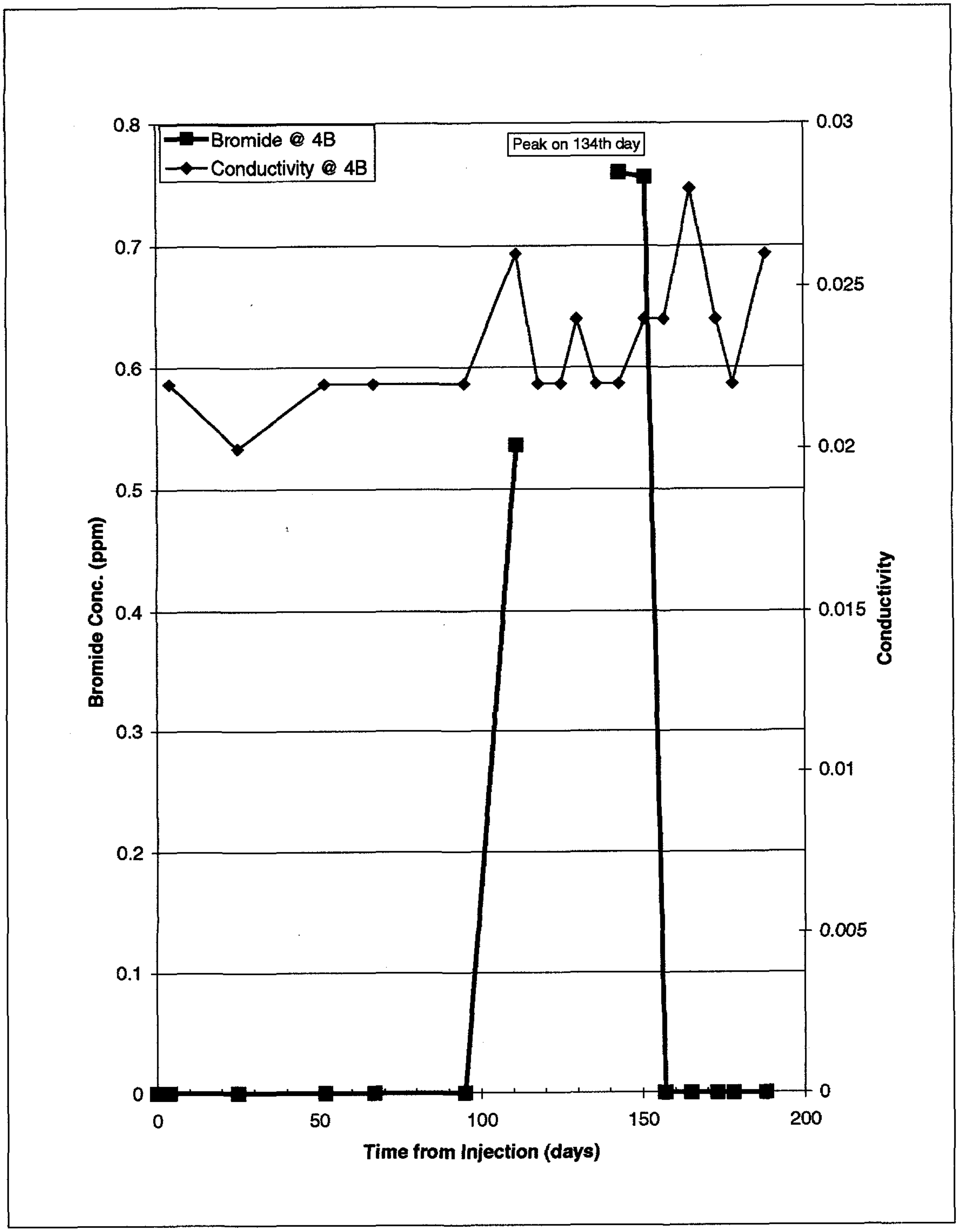

Figure 12: Bromide tracer concentration at SSM-004B

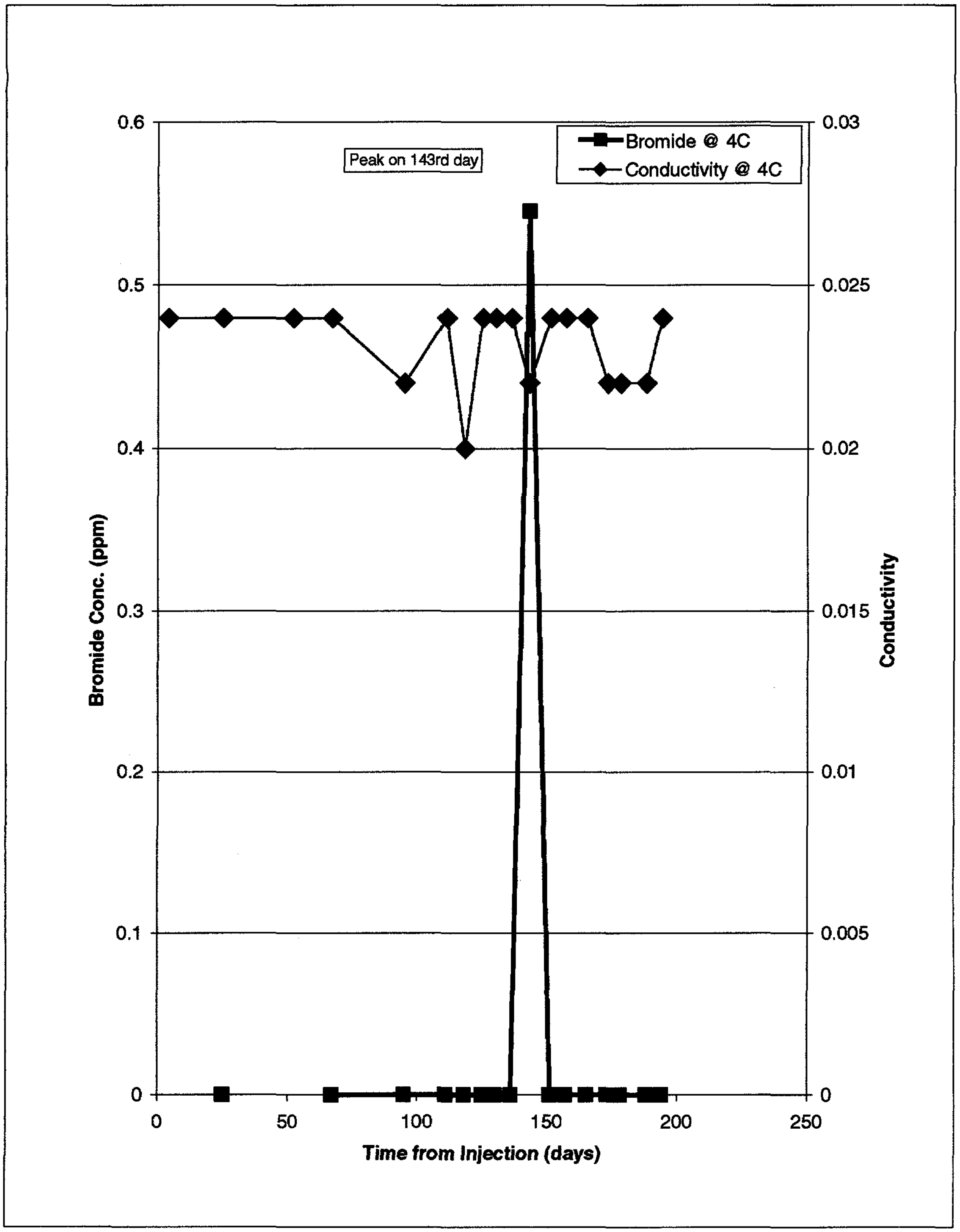

Figure 13: Bromide tracer concentration at SSM-004C

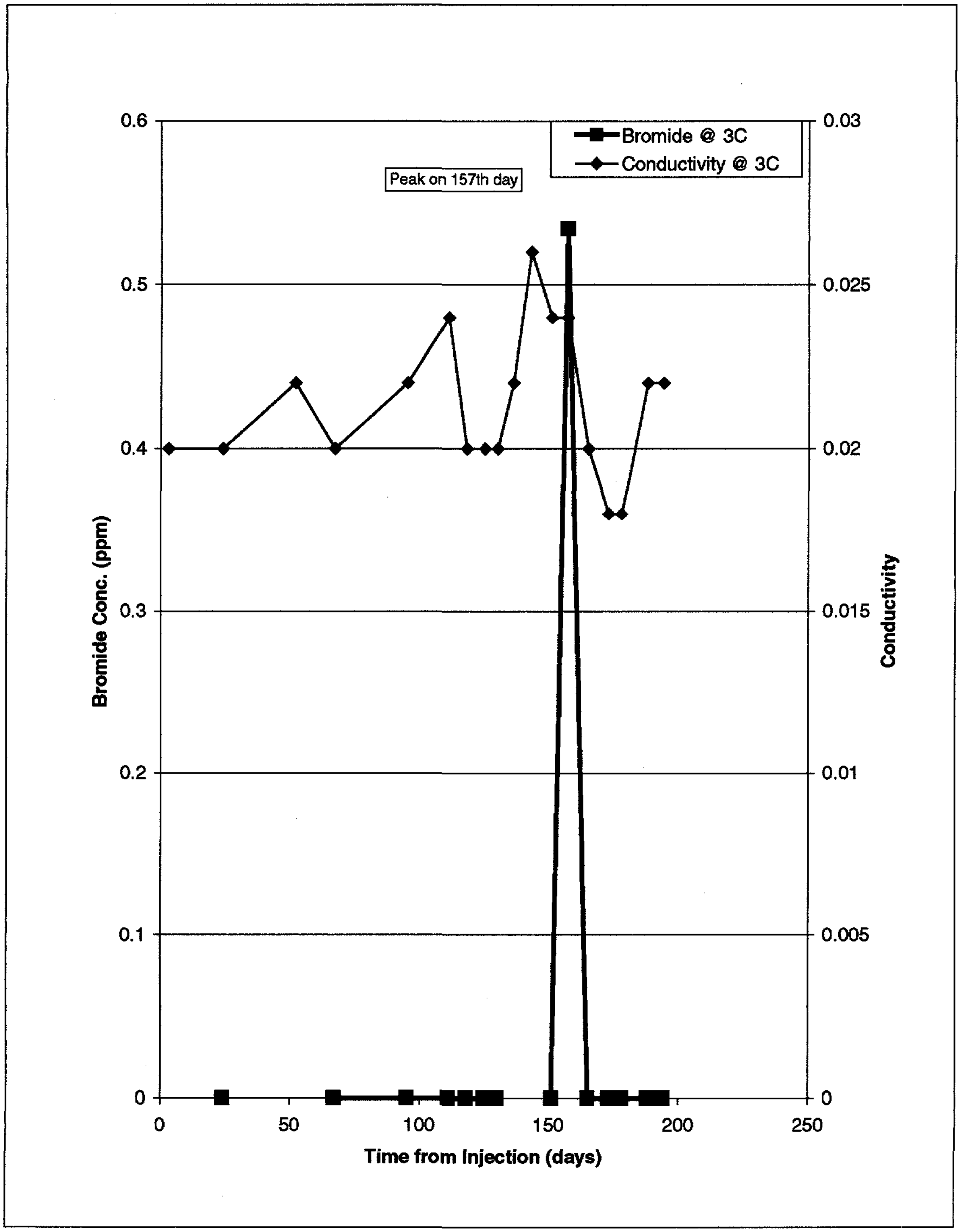

Figure 14: Bromide tracer concentration at SSM-003C

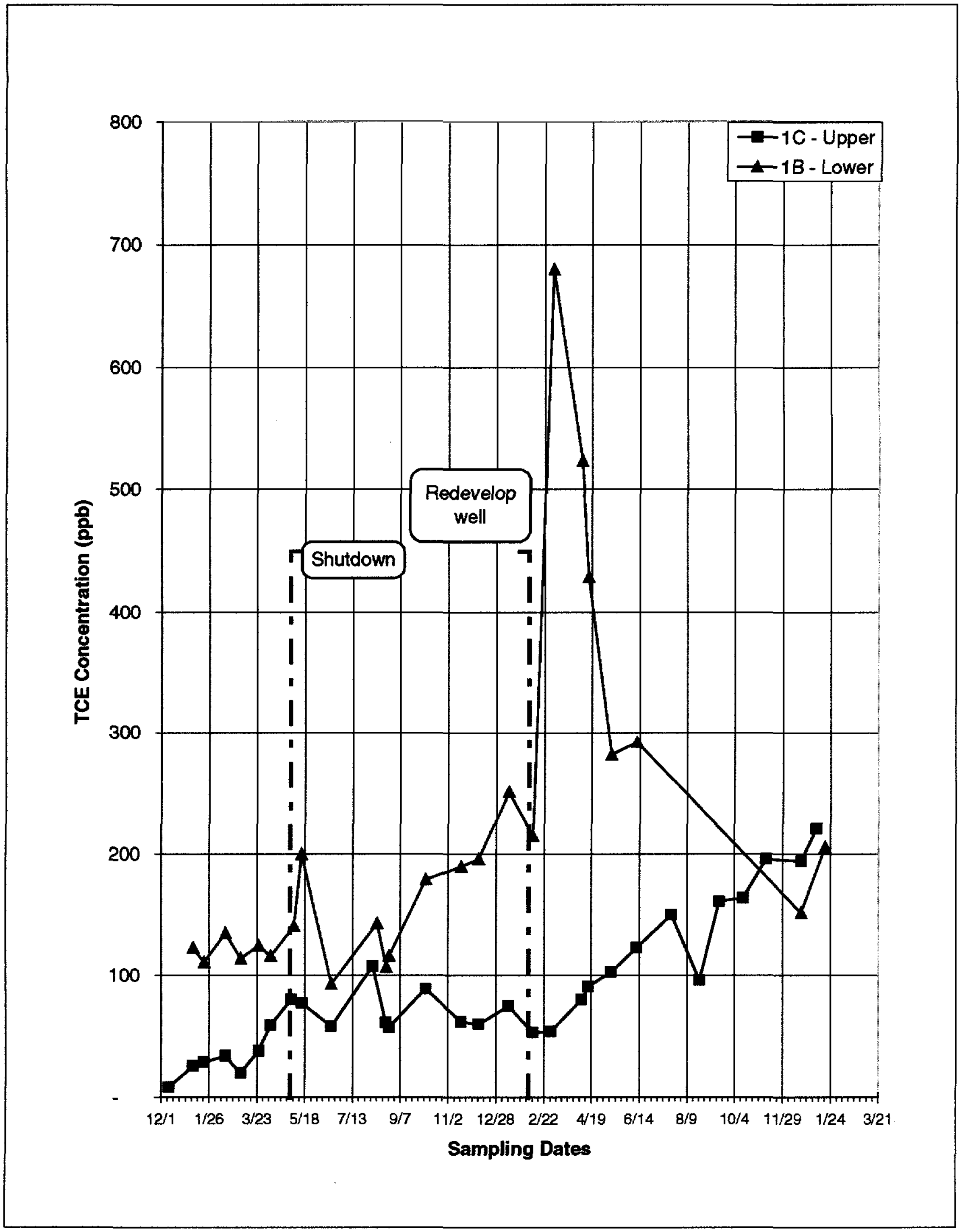

Figure 24: Groundwater sample analytical results – SSM-001

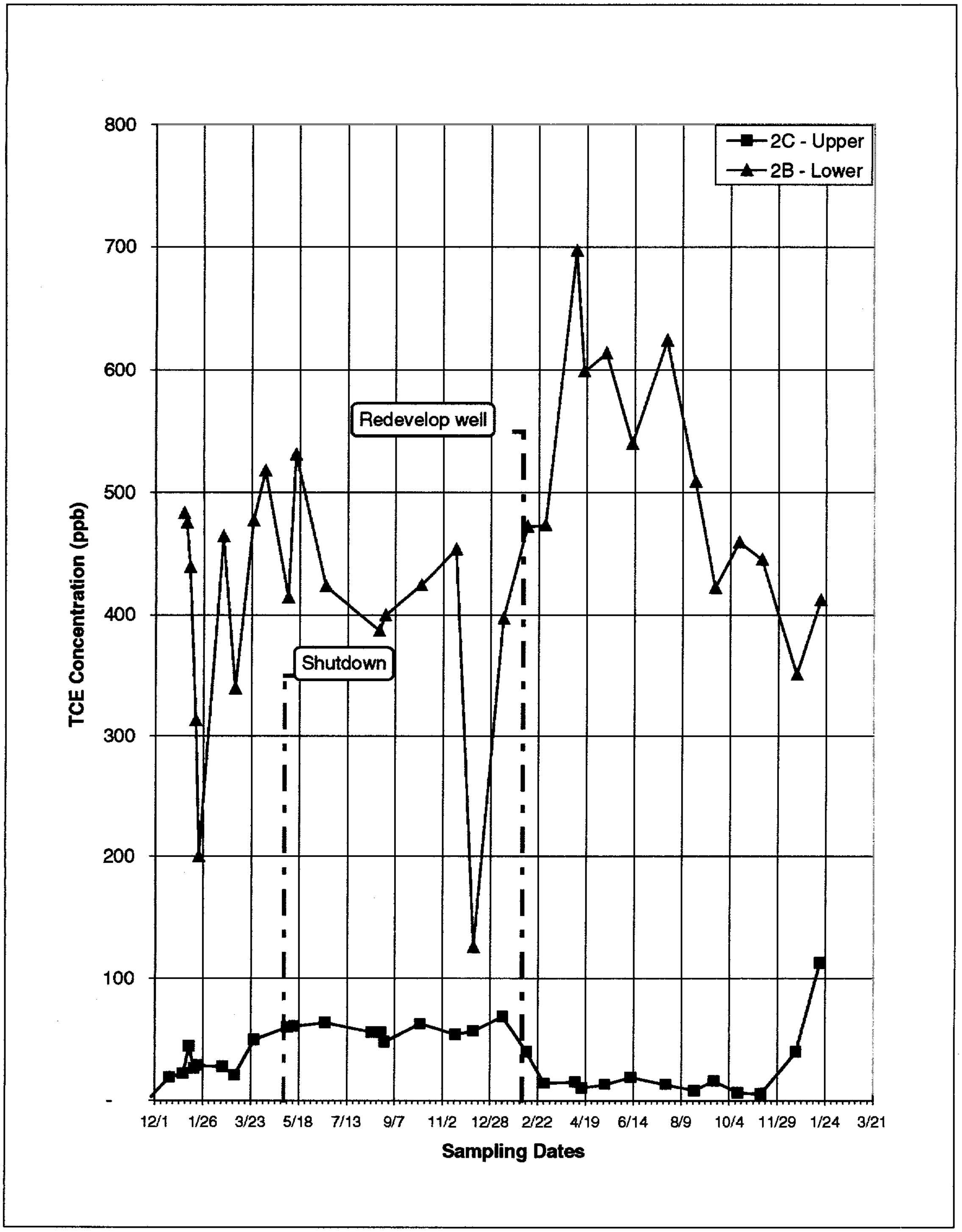

Figure 25: Groundwater sample analytical results – SSM-002

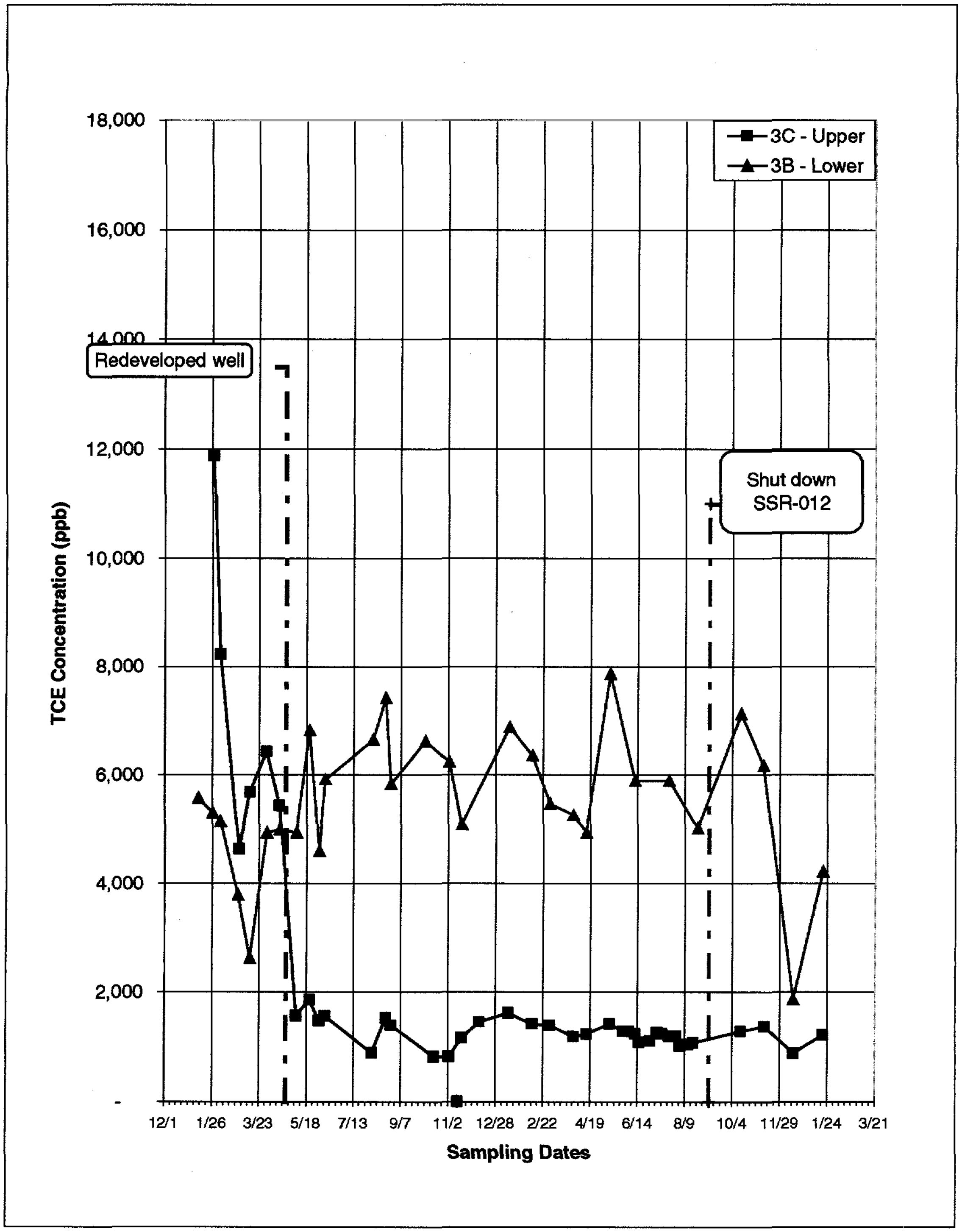

Figure 26: Groundwater sample analytical results – SSM-003

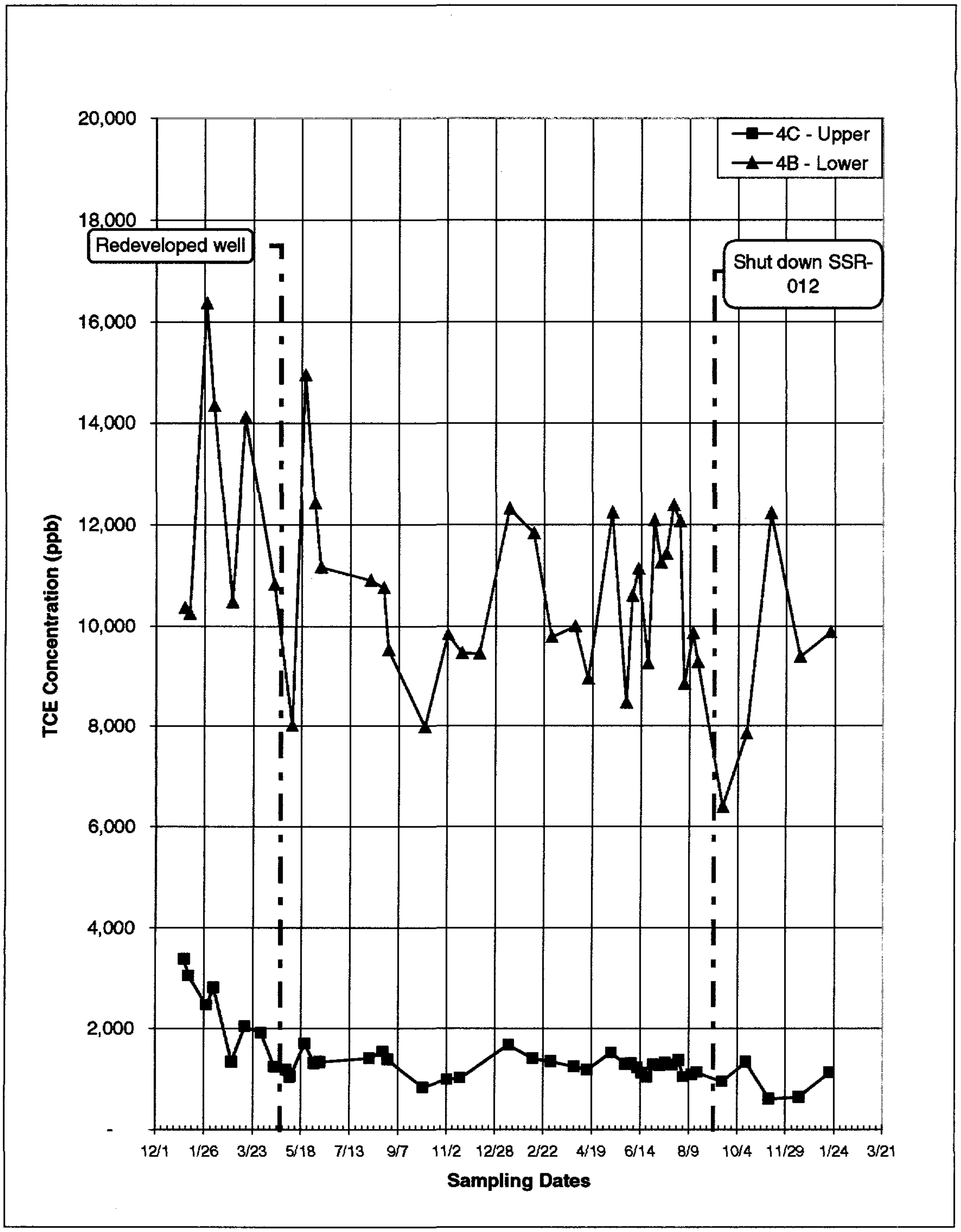

Figure 27: Groundwater sample analytical results – SSM-004

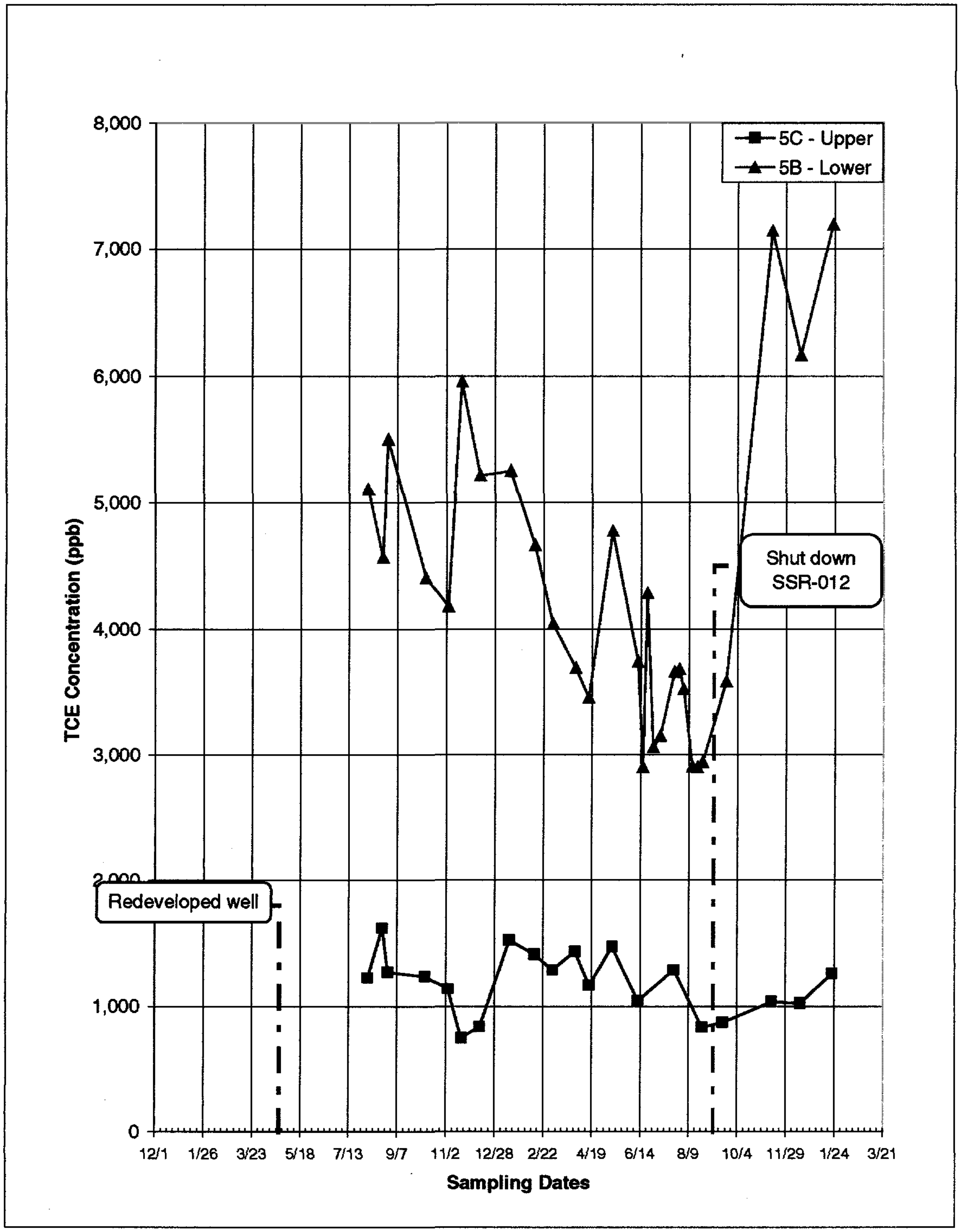

Figure 28: Groundwater sample analytical results – SSM-005

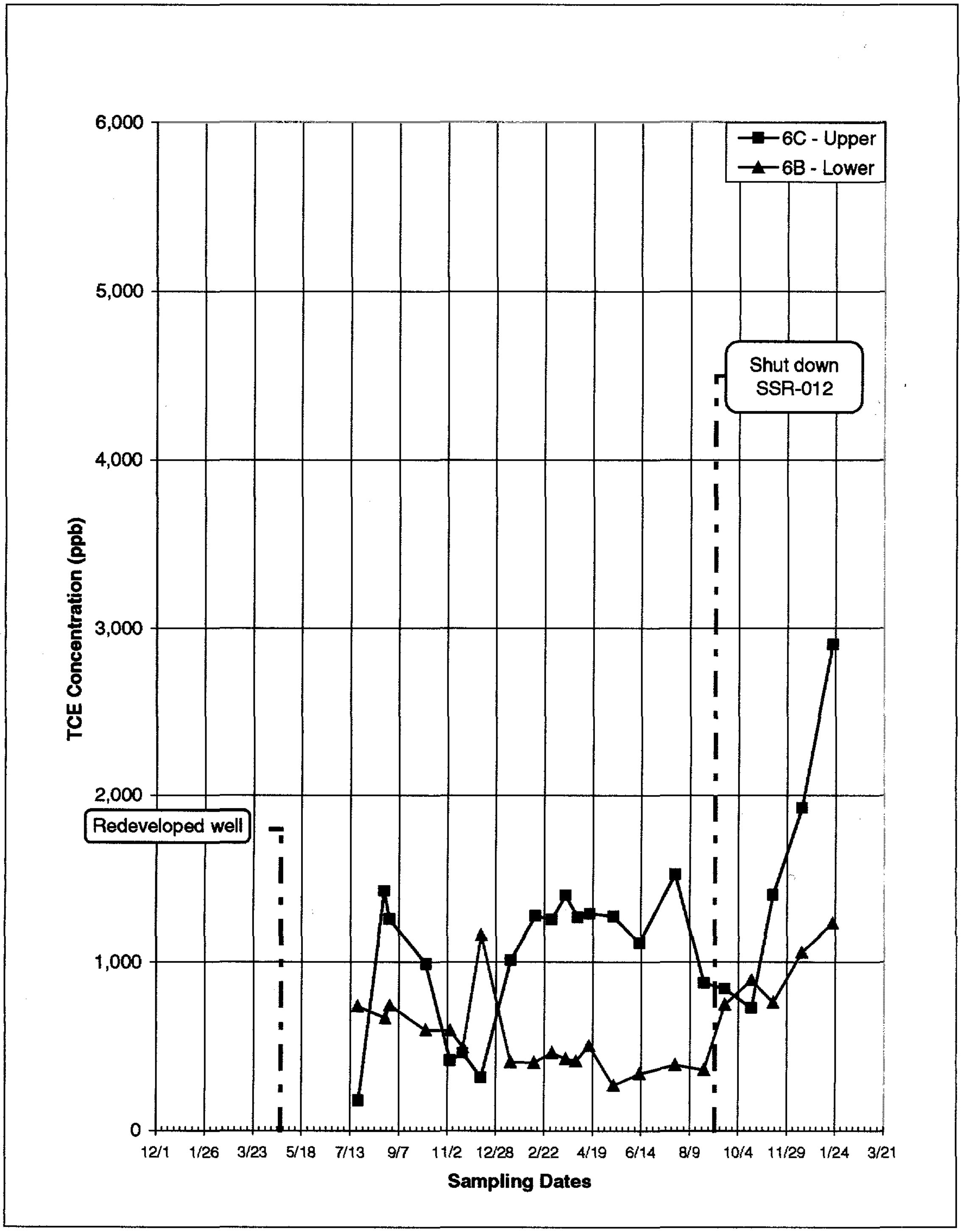

Figure 29: Groundwater sample analytical results – SSM-006

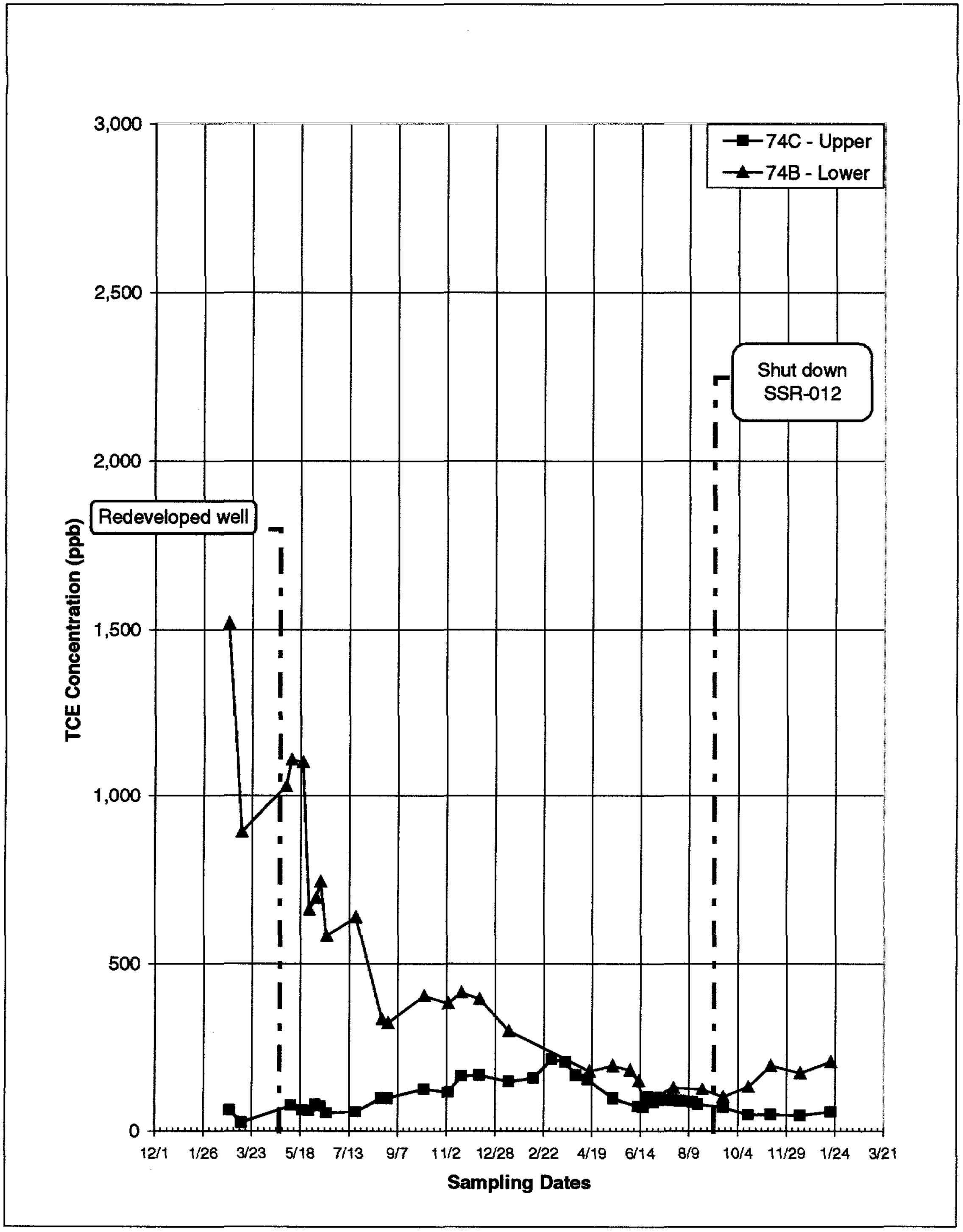

Figure 30: Groundwater sample analytical results – MSB-074

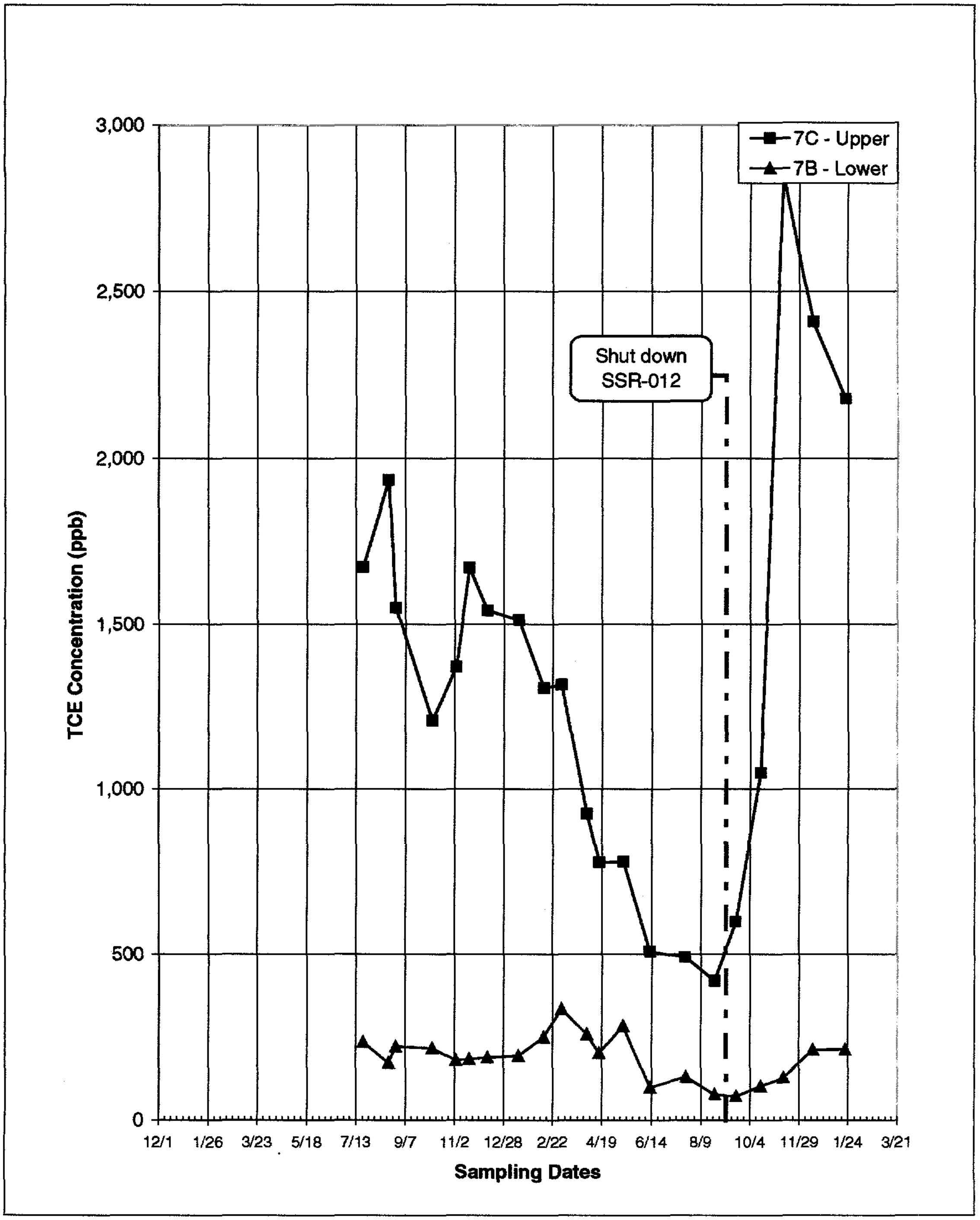

Figure 31: Groundwater sample analytical results – SSM-007

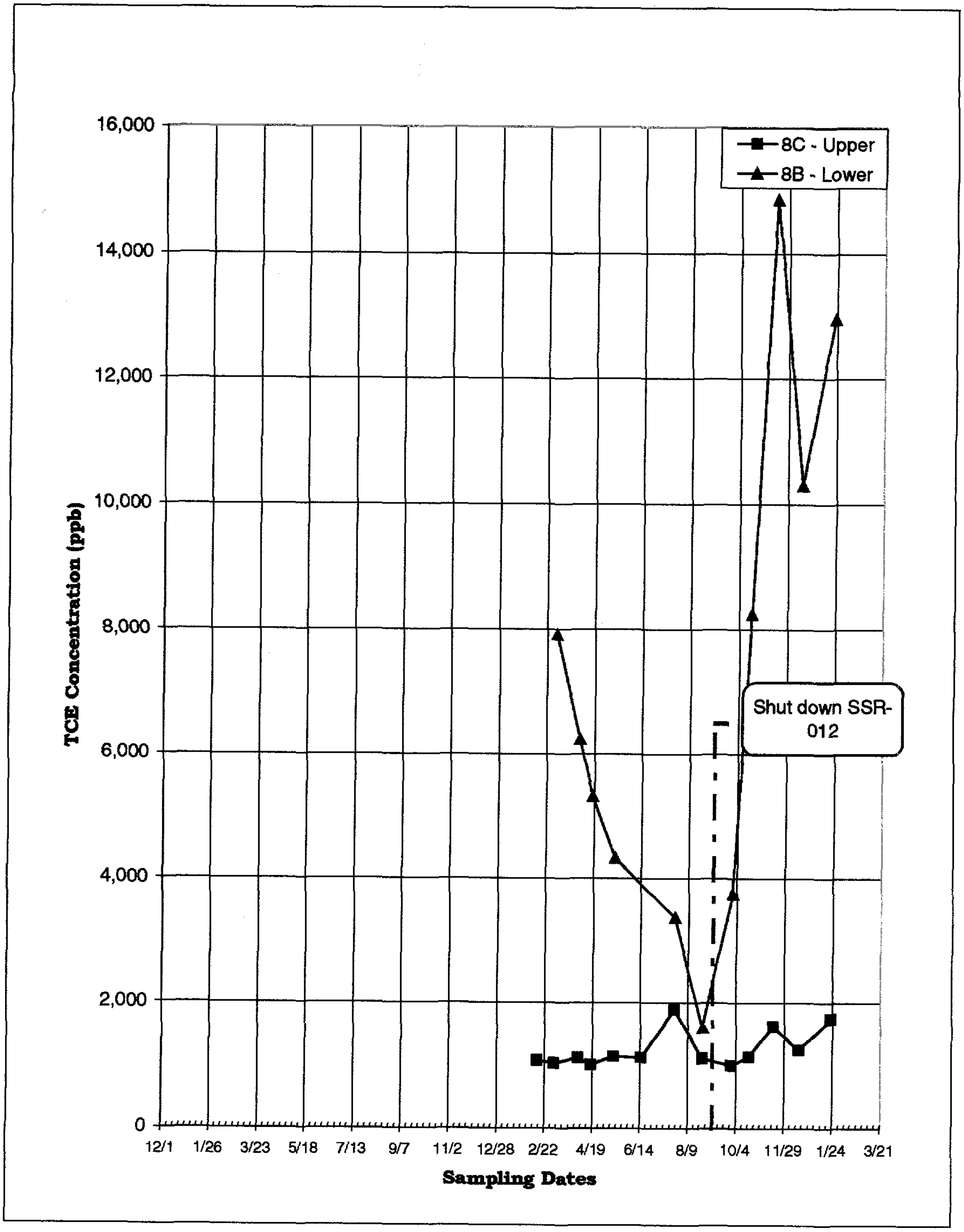

Figure 32: Groundwater sample analytical results – SSM-008

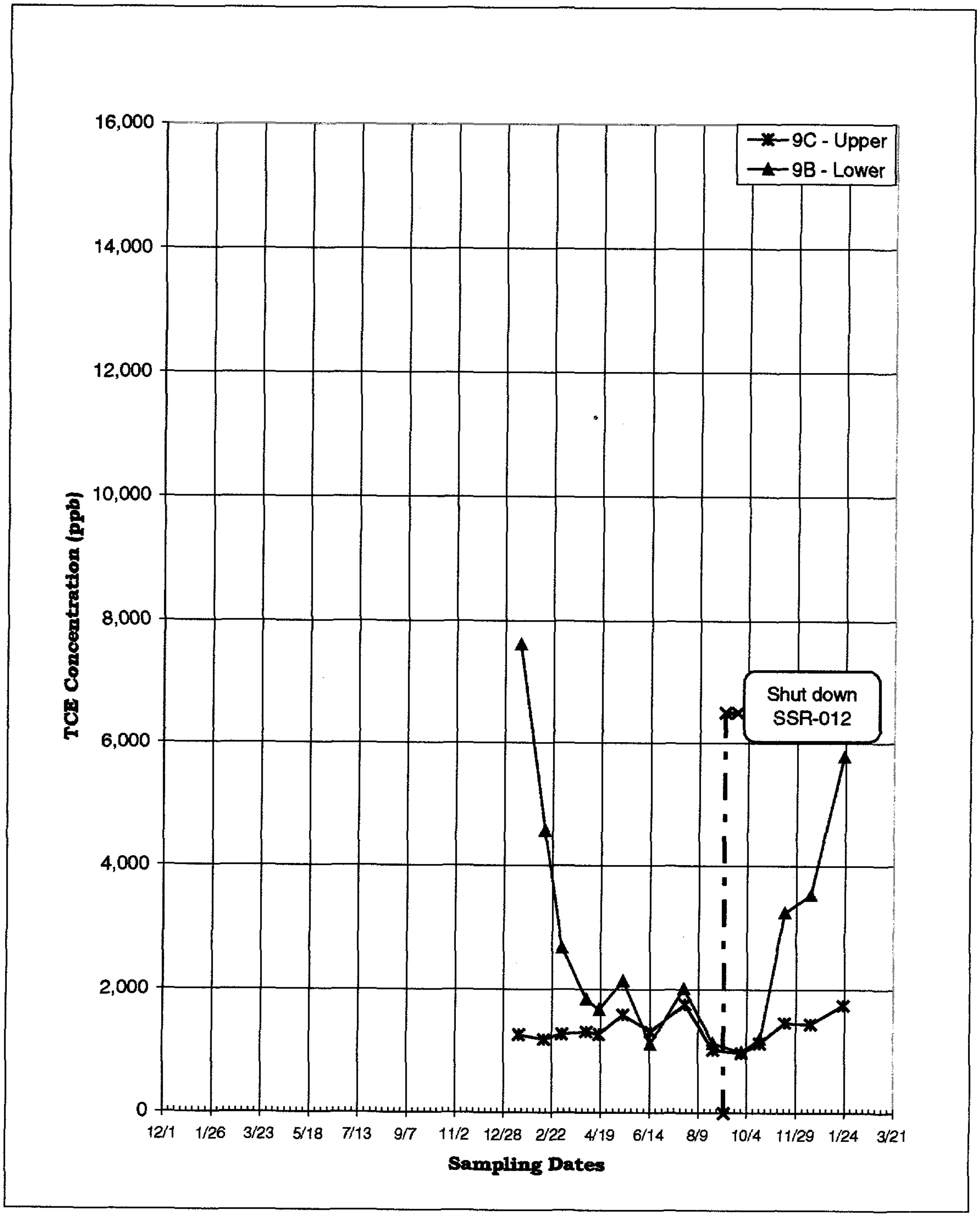

Figure 33: Groundwater sample analytical results – SSM-009

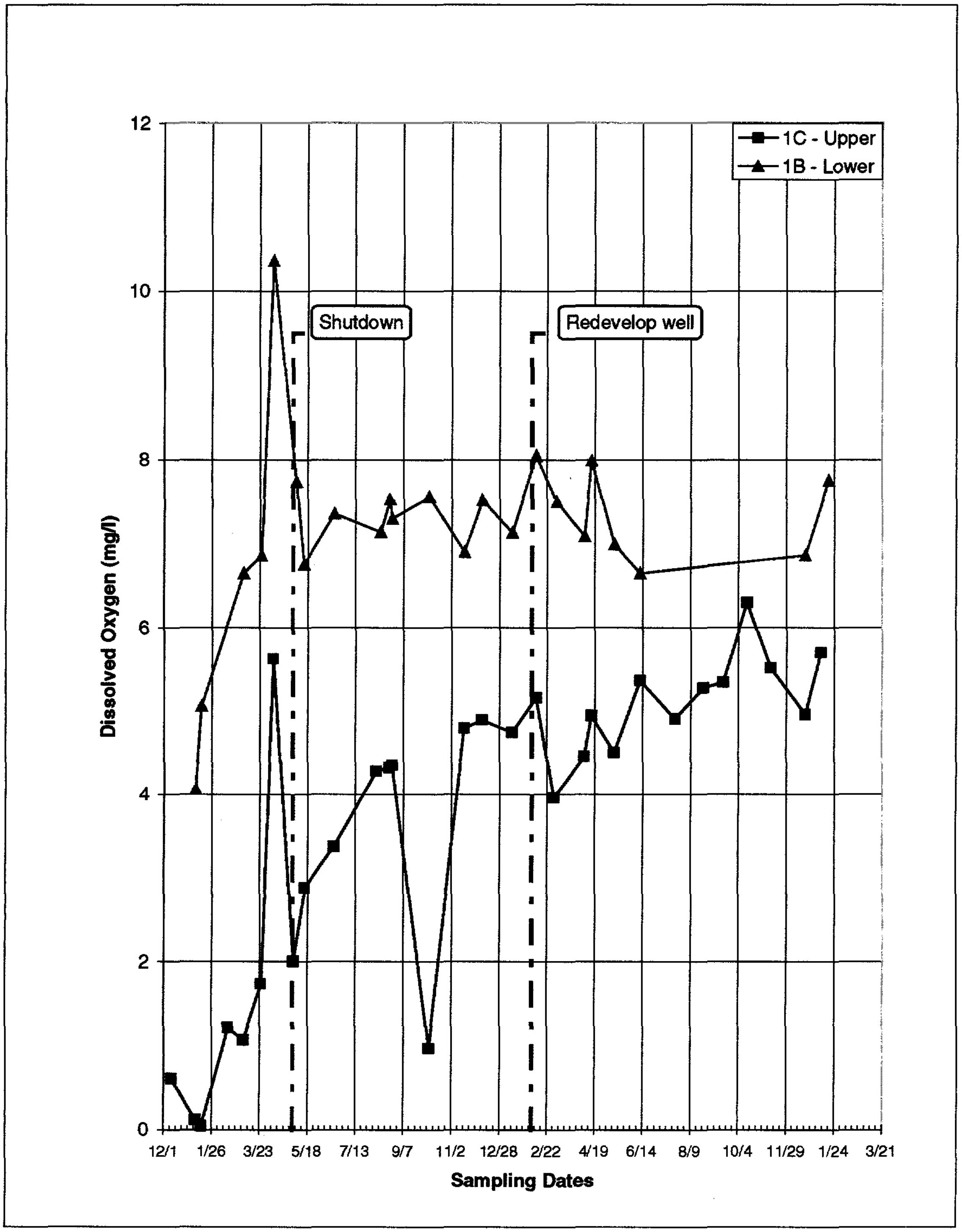

Figure 34: Dissolved Oxygen concentration – SSM-001

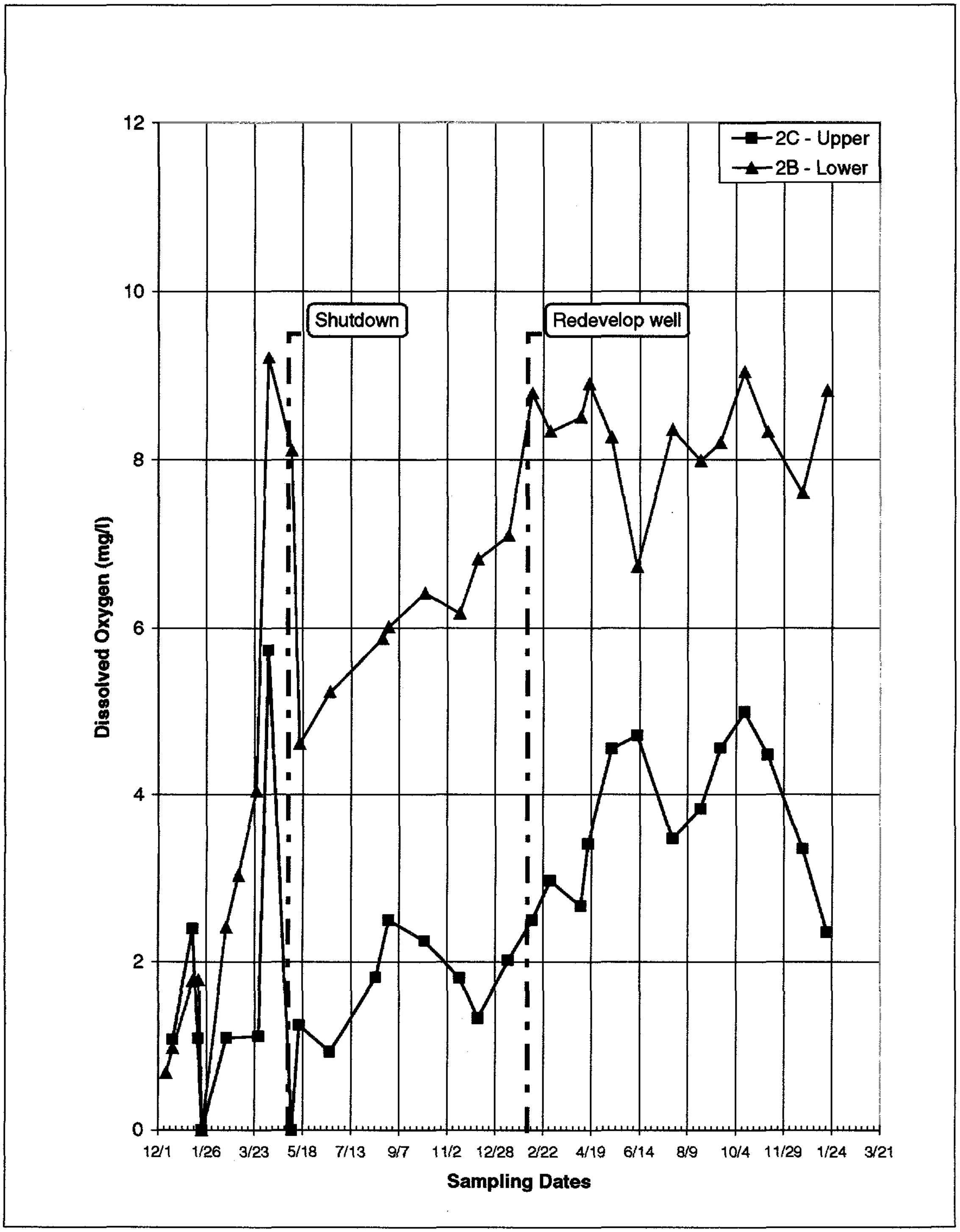

Figure 35: Dissolved Oxygen concentration – SSM-002

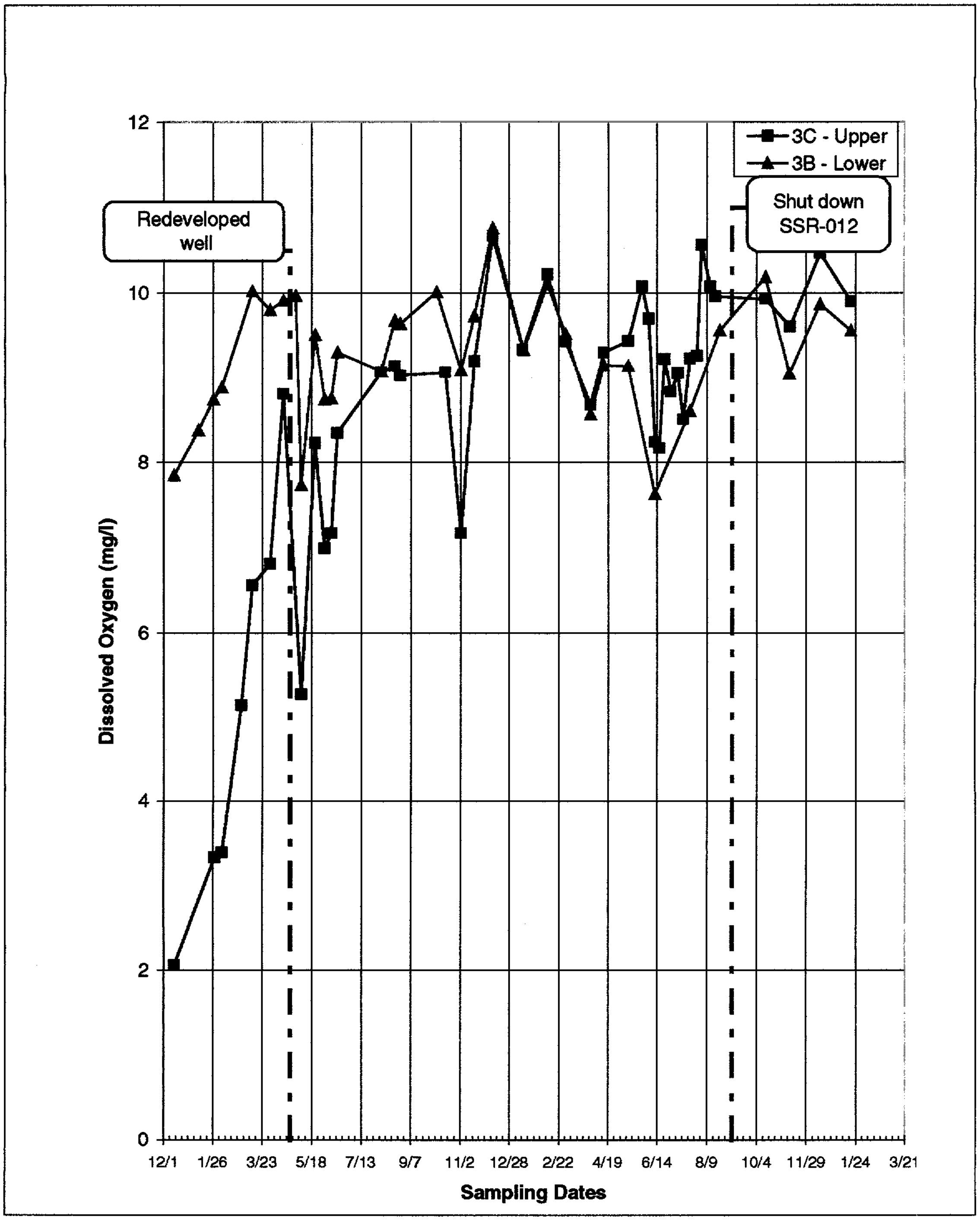

Figure 36: Dissolved Oxygen concentration – SSM-003

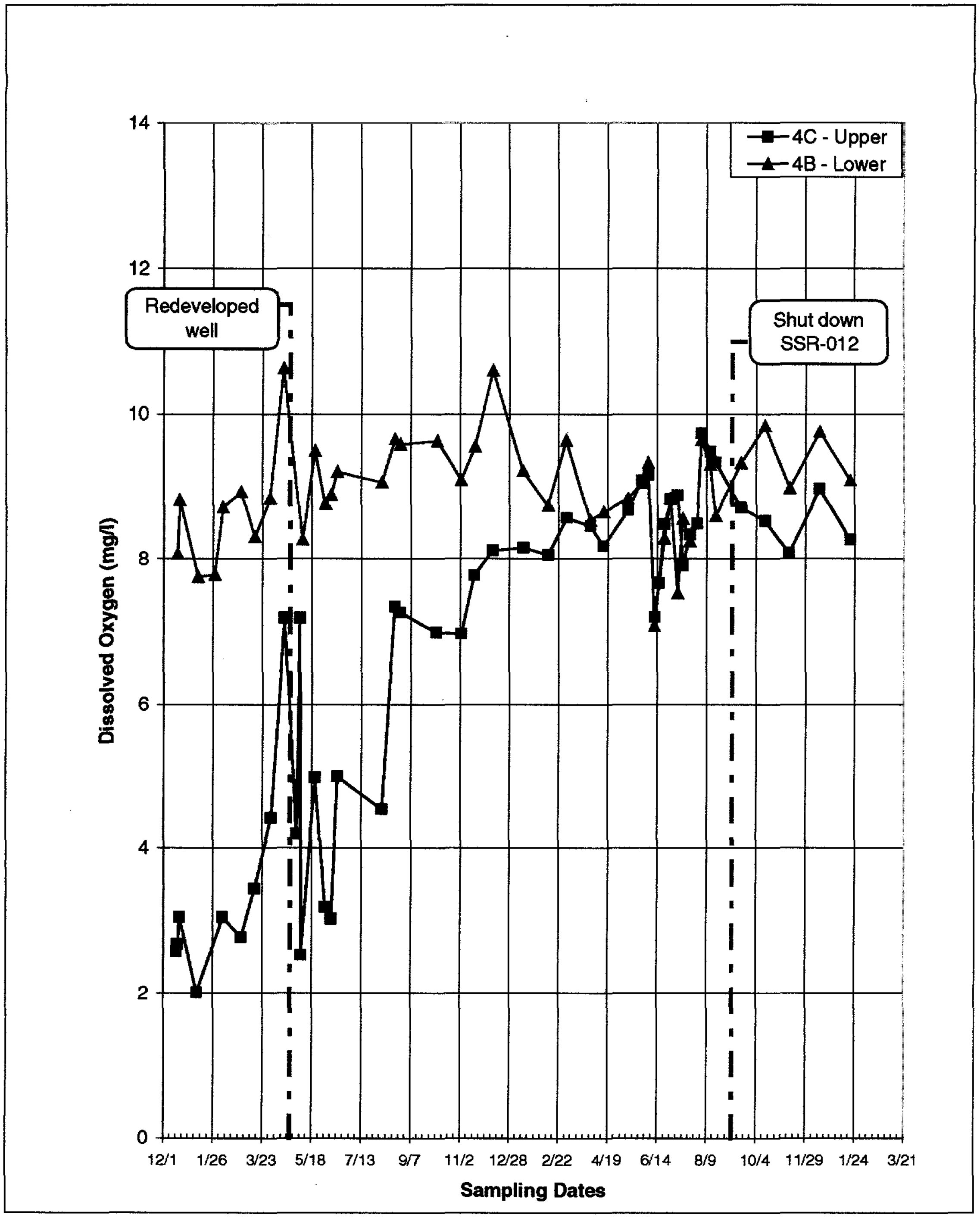

Figure 37: Dissolved Oxygen concentration – SSM-004

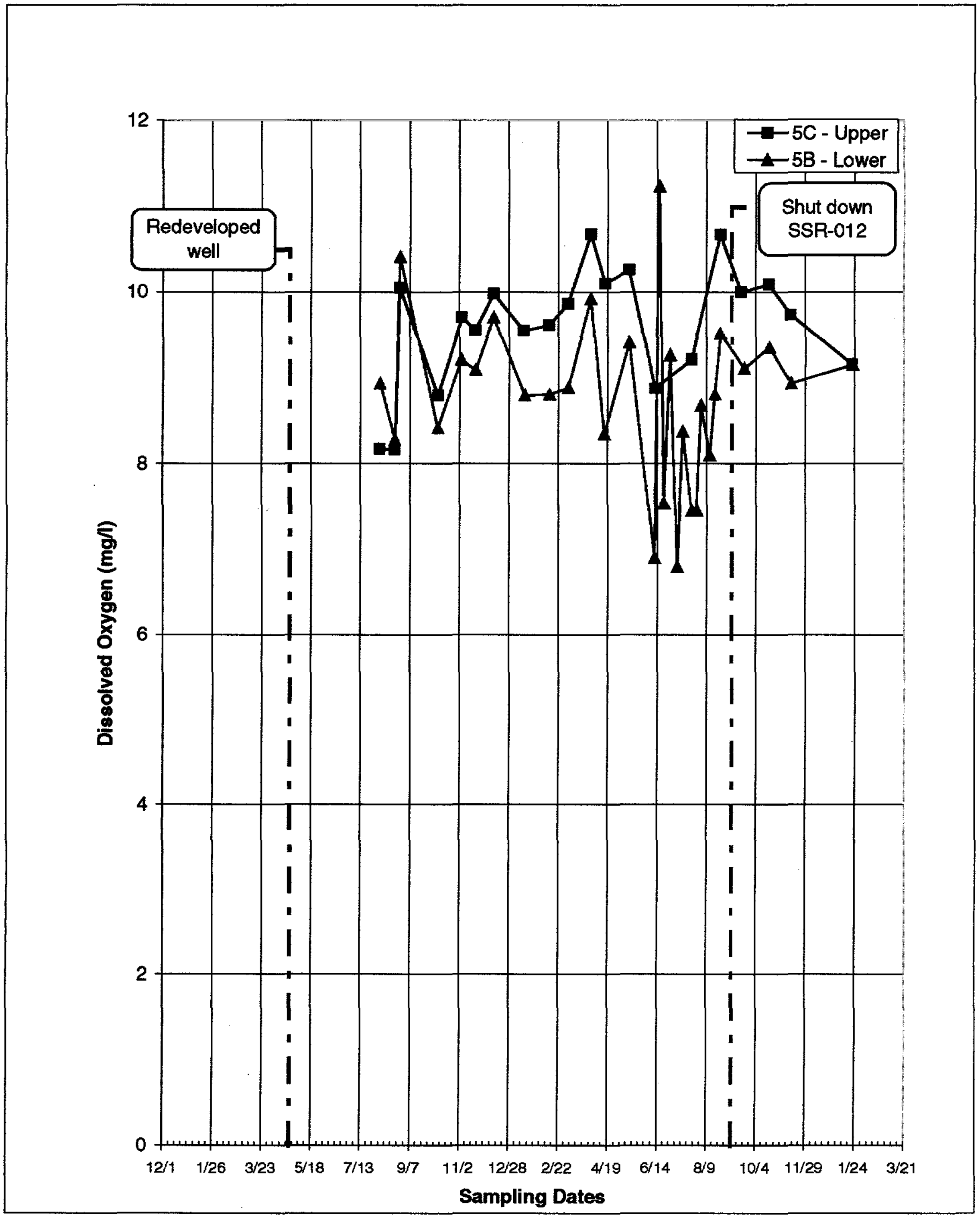

Figure 38: Dissolved Oxygen concentration – SSM-005

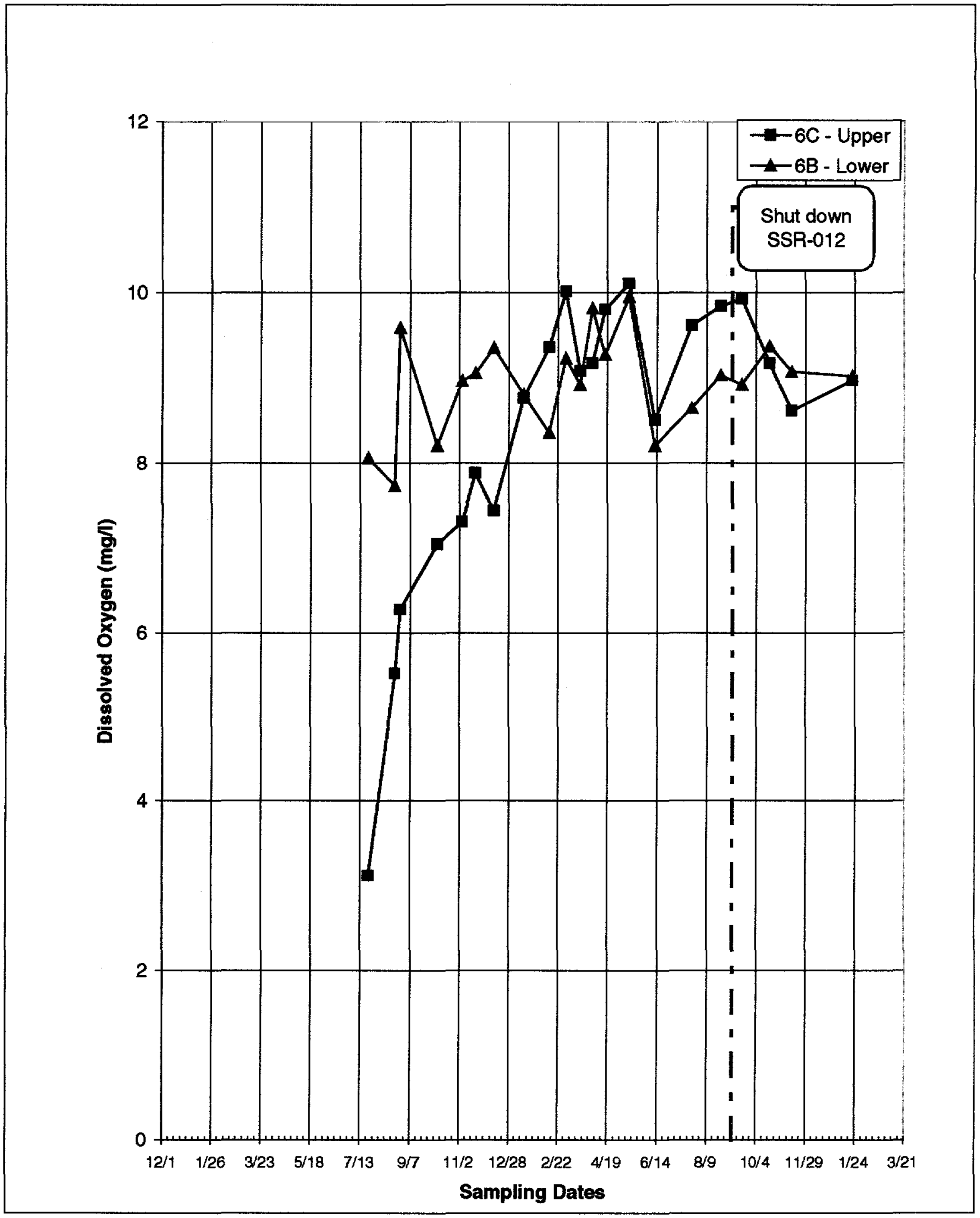

Figure 39: Dissolved Oxygen concentration – SSM-006

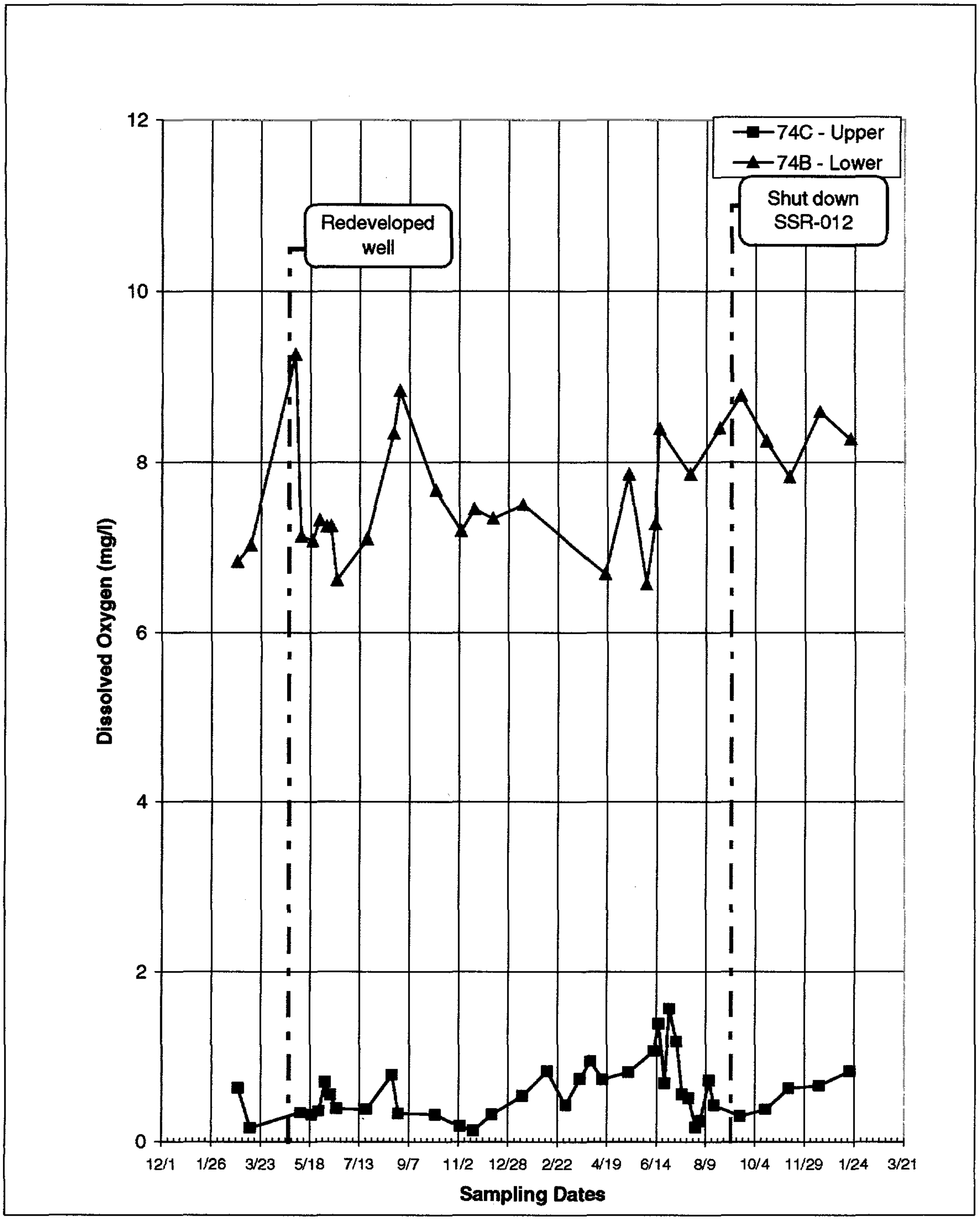

Figure 40: Dissolved Oxygen concentration – MSB-074

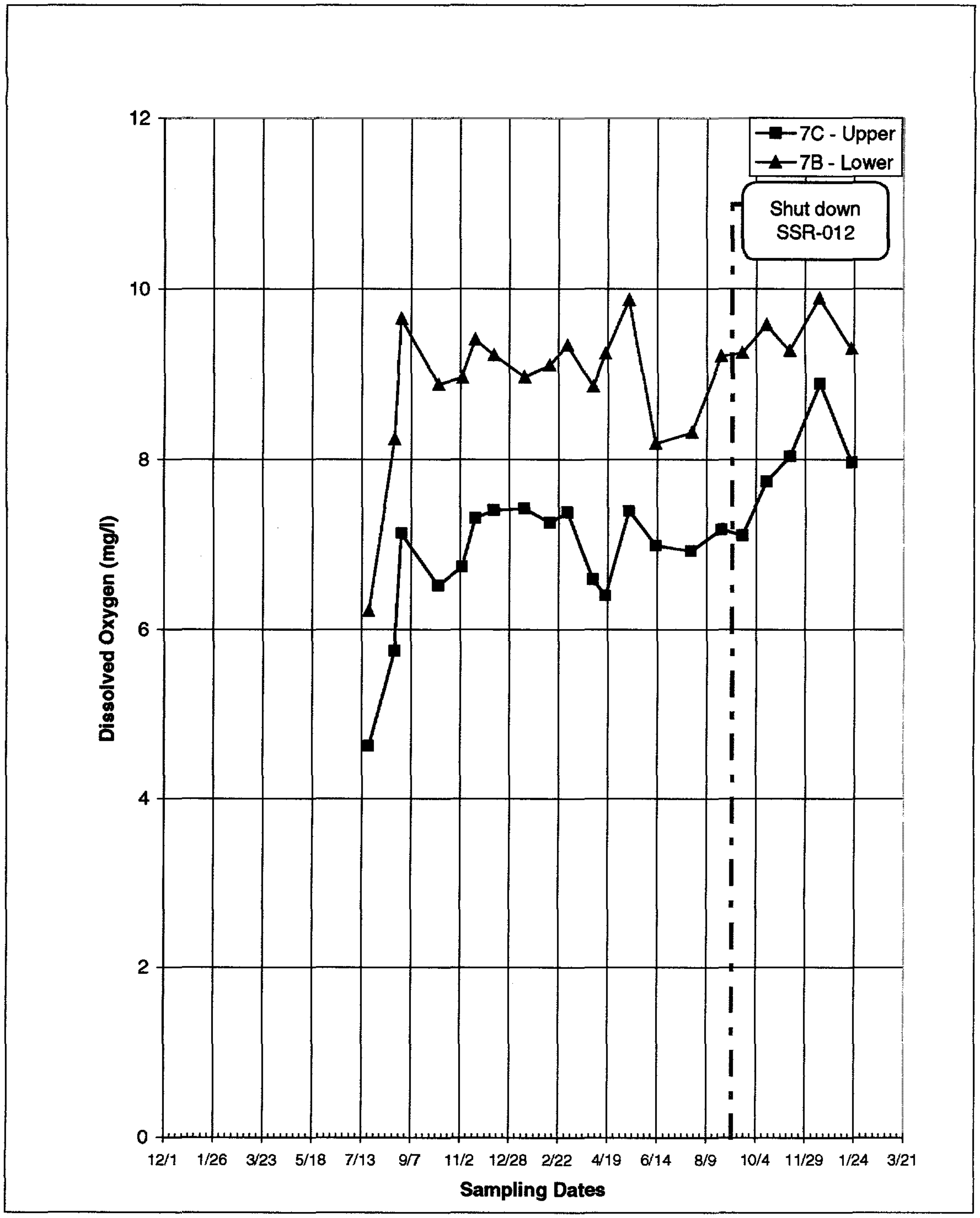

Figure 41: Dissolved Oxygen concentration – SSM-007

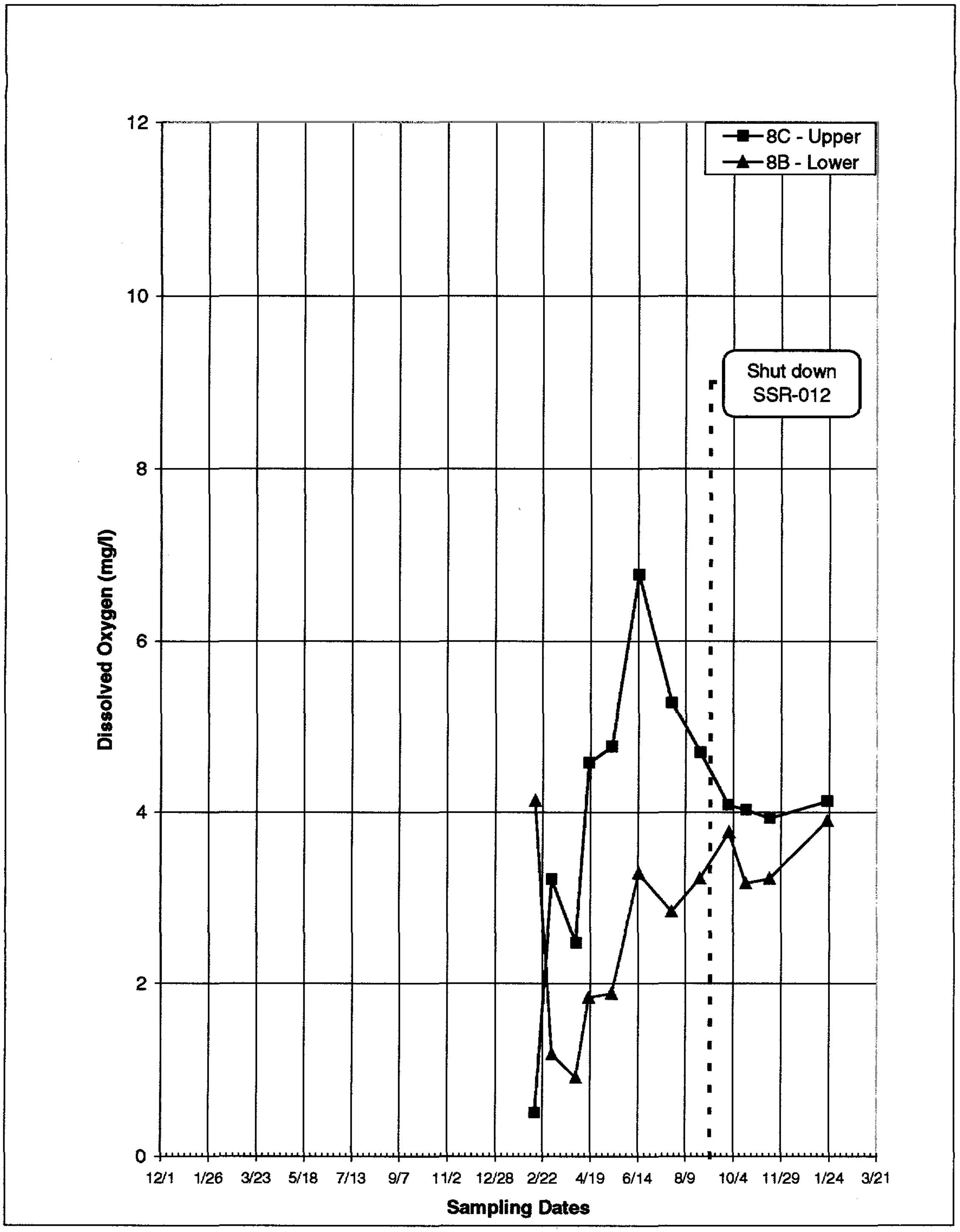

Figure 42: Dissolved Oxygen concentration – SSM-008

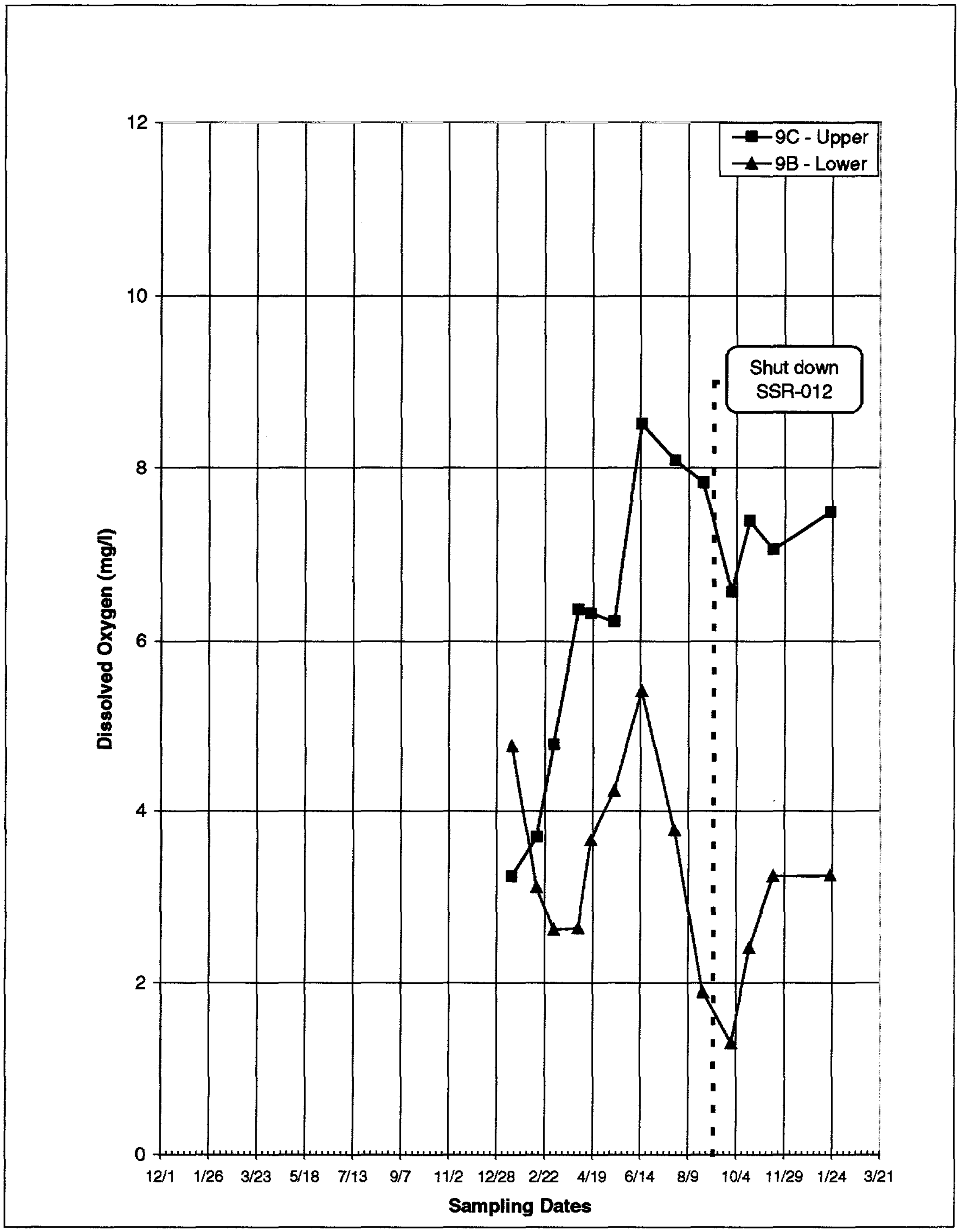

Figure 43: Dissolved Oxygen concentration – SSM-009

Table 4: Results of groundwater sampling – Wells SSM-001 and SSM-002

SSM-001 B			SSM-001 C			SSM-002 B			SSM-002 C		
	D.O.	TCE		D.O.	TCE		D.O.	TCE		D	TCE
Date	mg/L	ppb	Date	mg/L	ppb	Date	mg/L	ppb	Date	mg/L	ppb
12/10/96			12/10/96	0.6	8	12/10/96	0.7		11/27/96		3
1/7/97	4.1	123	1/7/97	0.1	26	12/18/96	1.0		12/18/96	1.1	19
1/14/97	5.1		1/14/97			1/3/97		483	1/3/97		22
1/20/97		111	1/20/97		29	1/6/97		475	1/10/97	2.4	45
2/14/97		135	2/14/97	1.2	34	1/10/97	1.8	439	1/16/97	1.1	27
3/4/97	6.7	114	3/4/97	1.1	20	1/17/97	1.8	313	1/21/97	N/A	29
3/25/97	6.9	125	3/25/97	1.7	38	1/21/97	N/A	200	2/18/97	1.1	28
4/8/97	10.4	116	4/8/97	5.6	59	2/18/97	2.4	464	3/4/97		21
5/5/97	7.7	141	5/2/97	2.0	80	3/4/97	3.0	339	3/27/97	1.1	50
5/14/97	6.8	200	5/15/97	2.9	77	3/25/97	4.0	477	4/8/97	5.7	
6/18/97	7.4	93	6/18/97	3.4	58	4/8/97	9.2	518	5/5/97	N/A	60
8/11/97	7.1	143	8/6/97	4.3	108	5/5/97	8.1	414	5/13/97	1.3	61
8/22/97	7.5	107	8/21/97	4.3	61	5/14/97	4.6	531	6/18/97	0.9	64
8/25/97	7.3	116	8/25/97	4.4	57	6/18/97	5.2	423	8/11/97	1.8	56
10/7/97	7.6	179	10/7/97	1.0	89	8/19/97	5.9	387	8/22/97		56
11/17/97	6.9	190	11/17/97	4.8	62	8/26/97	6.0	400	8/26/97	2.5	48
12/8/97	7.5	196	12/8/97	4.9	60	10/7/97	6.4	424	10/7/97	2.3	63
1/12/98	7.1	251	1/12/98	4.8	75	11/17/97	6.2	453	11/17/97	1.8	54
2/9/98	8.1	215	2/9/98	5.2	53	12/8/97	6.8	126	12/8/97	1.3	57
3/5/98	7.5	680	3/2/98	4.0	54	1/12/98	7.1	397	1/12/98	2.0	69
4/7/98	7.1	524	4/7/98	4.5	80	2/9/98	8.8	472	2/9/98	2.5	40
4/15/98	8.0	429	4/15/98	5.0	91	3/2/98	8.3	473	3/2/98	3.0	14
5/12/98	7.0	282	5/12/98	4.5	103	4/7/98	8.5	697	4/7/98	2.7	15
6/11/98	6.7	292	6/11/98	5.4	123	4/16/98	8.9	599	4/15/98	3.4	10
12/21/98	6.9	152	7/22/98	4.9	150	5/12/98	8.3	614	5/12/98	4.6	13
1/18/99	7.8	206	8/24/98	5.3	96	6/11/98	6.7	540	6/11/98	4.7	19
			9/16/98	5.4	161	7/22/98	8.4	624	7/22/98	3.5	13
			10/14/98	6.3	164	8/24/98	8.0	509	8/24/98	3.8	8
			11/10/98	5.5	196	9/16/98	8.2	422	9/16/98	4.6	16
			12/21/98	5.0	194	10/14/98	9.0	459	10/14/98	5.0	6
			1/8/99	5.7	221	11/10/98	8.3	445	11/10/98	4.5	5
						12/21/98	7.6	351	12/21/98	3.4	40
						1/18/99	8.8	412	1/18/99	2.4	113

Table 5: Results of groundwater sampling – Wells SSM-003 and SSM-004

SSM-003 B			SSM-003 C			SSM-004 B			SSM-004 C		
	D.O.	TCE		D.O.	TCE		D.O.	TCE		D.O.	TCE
Date	mg/L	ppb	Date	mg/L	ppb	Date	mg/L	ppb	Date	mg/L	ppb
12/13/96	7.9		12/13/96	2.1		12/17/96	8.1		12/16/96	2.6	
1/10/97	8.4	5,576	1/28/97	3.3	11,882	12/19/96	8.8		12/17/96	2.7	
1/27/97	8.8	5,304	2/5/97	3.4	8,226	1/3/97		10,364	12/19/96	3.0	
2/5/97	8.9	5,148	2/27/97	5.1	4,638	1/9/97	7.8	10,249	1/3/97		3,386
2/26/97		3,792	3/12/97	6.6	5,687	1/28/97	7.8	16,370	1/8/97	2.0	3,055
3/12/97	10.0	2,630	4/1/97	6.8	6,437	2/6/97	8.7	14,342	1/29/97		2,470
4/1/97	9.8	4,942	4/16/97	8.8	5,436	2/27/97	8.9	10,479	2/6/97	3.0	2,820
4/16/97	9.9	4,998	5/6/97	5.3	1,574	3/14/97	8.3	14,110	2/27/97	2.8	1,334
4/30/97	10.0		5/22/97	8.2	1,861	4/1/97	8.8		3/14/97	3.4	2,042
5/6/97	7.7	4,942	6/2/97	7.0	1,481	4/16/97	10.6	10,823	4/2/97	4.4	1,920
5/22/97	9.5	6,827	6/9/97	7.2	1,569	5/7/97	8.3	8,014	4/17/97	7.2	1,249
6/2/97	8.8	4,597	6/16/97	8.4		5/22/97	9.5	14,952	5/1/97	4.2	1,183
6/9/97	8.8	5,920	8/4/97	9.1	889	6/2/97	8.8	12,417	5/5/97	7.2	1,035
6/16/97	9.3		8/20/97	9.1	1,531	6/9/97	8.9	11,164	5/6/97	2.5	1,063
8/5/97	9.1	6,655	8/26/97	9.0	1,400	6/16/97	9.2		5/22/97	5.0	1,708
8/20/97	9.7	7,415	10/16/97	9.1	827	8/5/97	9.1	10,912	6/2/97	3.2	1,322
8/26/97	9.6	5,836	11/3/97	7.2	824	8/20/97	9.7	10,756	6/9/97	3.0	1,339
10/6/97	10.0	6,625	11/18/97	9.2	1,167	8/26/97	9.6	9,521	6/16/97	5.0	
11/3/97	9.1	6,242	12/9/97	10.7	1,459	10/7/97	9.6	7,973	8/5/97	4.5	1,411
11/18/97	9.7	5,087	1/12/98	9.3	1,623	11/3/97	9.1	9,831	8/20/97	7.4	1,546
12/9/97	10.8		2/9/98	10.2	1,419	11/19/97	9.6	9,463	8/26/97	7.3	1,393
1/13/98	9.3	6,886	3/2/98	9.4	1,393	12/9/97	10.6	9,447	10/6/97	7.0	837
2/9/98	10.1	6,359	3/30/98	8.7	1,189	1/13/98	9.2	12,318	11/3/97	7.0	997
3/2/98	9.5	5,471	4/14/98	9.3	1,234	2/10/98	8.7	11,831	11/18/97	7.8	1,024
3/30/98	8.6	5,264	5/12/98	9.4	1,424	3/3/98	9.6	9,782	12/9/97	8.1	
4/14/98	9.2	4,932	5/28/98	10.1	1,286	3/30/98	8.5	9,998	1/13/98	8.2	1,675
5/12/98	9.1	7,867	6/4/98	9.7	1,289	4/14/98	8.7	8,947	2/10/98	8.1	1,407
6/11/98	7.6	5,893	6/11/98	8.2	1,248	5/12/98	8.8	12,234	3/3/98	8.6	1,349
7/21/98	8.6	5,894	6/16/98	8.2	1,082	5/28/98	9.1	8,466	3/30/98	8.5	1,254
8/24/98	9.6	5,017	6/22/98	9.2		6/4/98	9.3	10,592	4/14/98	8.2	1,186
10/14/98	10.2	7,130	6/29/98	8.8	1,110	6/11/98	7.1	11,127	5/12/98	8.7	1,517
11/10/98	9.1	6,175	7/7/98	9.1	1,270	6/22/98	8.3	9,250	5/28/98	9.1	1,297
12/15/98	9.9	1,866	7/13/98	8.5	1,248	6/29/98	8.8	12,090	6/4/98	9.2	1,303
1/19/99	9.6	4,223	7/21/98	9.2	1,198	7/7/98	7.5	11,255	6/11/98	7.2	1,231
			7/29/98	9.3	1,192	7/13/98	8.6	11,420	6/16/98	7.7	1,119
			8/3/98	10.6	1,010	7/21/98	8.3	12,376	6/22/98	8.5	1,035
			8/13/98	10.1	1,041	7/29/98	8.5	12,063	6/29/98	8.8	1,287
			8/19/98	10.0	1,074	8/3/98	9.7	8,834	7/7/98	8.9	1,273
			10/14/98	9.9	1,282	8/13/98	9.3	9,856	7/13/98	7.9	1,320
			11/11/98	9.6	1,372	8/19/98	8.6	9,273	7/21/98	8.3	1,279
			12/15/98	10.5	882	9/17/98	9.3	6,396	7/29/98	8.5	1,372
			1/19/99	9.9	1,214	10/14/98	9.8	7,847	8/3/98	9.7	1,045
						11/11/98	9.0	12,229	8/13/98	9.5	1,091
						12/15/98	9.8	9,382	8/19/98	9.3	1,140
						1/19/99	9.1	9,882	9/17/98	8.7	950
									10/14/98	8.5	1,332
									11/10/98	8.1	611
									12/15/98	9.0	644
									1/19/99	8.3	1,135

Table 6: Results of groundwater sampling – Wells MSB-074 and SSM-005

MSB-074B			MSB-074 C			SSM-005 B			SSM-005 C		
	D.O.	TCE		D.O.	TCE		D.O.	TCE		D.O.	TCE
Date	mg/L	ppb	Date	mg/L	ppb	Date	mg/L	ppb	Date	mg/L	ppb
2/24/97	6.8	1,522	2/25/97	0.6	64	8/4/97	8.9	5,107	8/4/97	8.2	1,229
3/11/97	7.0	894	3/11/97	0.2	27	8/21/97	8.3	4,565	8/21/97	8.2	1,620
5/1/97	9.3	1,030	5/7/97	0.3	77	8/27/97	10.4	5,501	8/27/97	10.1	1,276
5/7/97	7.1	1,109	5/20/97	0.3	64	10/9/97	8.4	4,407	10/9/97	8.8	1,241
5/20/97	7.1	1,101	5/28/97	0.4	62	11/4/97	9.2	4,180	11/5/97	9.7	1,138
5/28/97	7.3	662	6/4/97	0.7	80	11/20/97	9.1	5,957	11/20/97	9.6	750
6/5/97	7.2	696	6/10/97	0.6	76	12/11/97	9.7	5,218	12/11/97	10.0	840
6/10/97	7.3	745	6/17/97	0.4	55	1/15/98	8.8	5,252	1/14/98	9.6	1,523
6/17/97	6.6	583	7/21/97	0.4	58	2/12/98	8.8	4,663	2/12/98	9.6	1,413
7/21/97	7.1	639	8/19/97	0.8	99	3/5/98	8.9	4,045	3/5/98	9.9	1,290
8/20/97	8.3	334	8/26/97	0.3	99	3/31/98	9.9	3,690	3/31/98	10.7	1,434
8/27/97	8.8	324	10/7/97	0.3	127	4/15/98	8.3	3,454	4/16/98	10.1	1,168
10/7/97	7.7	405	11/4/97	0.2	117	5/13/98	9.4	4,776	5/13/98	10.3	1,471
11/4/97	7.2	382	11/19/97	0.1	166	6/11/98	6.9	3,741	6/12/98	8.9	1,043
11/19/97	7.5	414	12/10/97	0.3	169	6/17/98	11.2	2,901	7/23/98	9.2	1,289
12/10/97	7.3	395	1/13/98	0.5	149	6/22/98	7.5	4,283	8/25/98	10.7	837
1/13/98	7.5	300	2/10/98	0.8	160	6/29/98	9.3	3,057	9/18/98	10.0	873
4/16/98	6.7	180	3/3/98	0.4	216	7/7/98	6.8	3,149	10/19/98	10.1	
5/13/98	7.9	196	3/19/98	0.7	208	7/13/98	8.4		11/13/98	9.7	1,036
6/2/98	6.6	183	3/31/98	1.0	168	7/23/98	7.5	3,662	12/16/98	0.0	1,025
6/12/98	7.3	151	4/14/98	0.7	155	7/29/98	7.5	3,683	1/21/99	9.2	1,260
6/17/98	8.4	88	5/13/98	0.8	100	8/3/98	8.7	3,522			
7/22/98	7.9	130	6/11/98	1.1	75	8/13/98	8.1	2,904			
8/24/98	8.4	126	6/17/98	1.4	71	8/19/98	8.8	2,902			
9/17/98	8.8	103	6/23/98	0.7	103	8/25/98	9.5	2,939			
10/16/98	8.3	133	6/29/98	1.6	88	9/21/98	9.1	3,584			
11/11/98	7.8	196	7/7/98	1.2	101	10/19/98	9.4				
12/15/98	8.6	175	7/13/98	0.6	94	11/13/98	8.9	7,141			
1/19/99	8.3	208	7/21/98	0.5	92	12/16/98	0.0	6,164			
			7/29/98	0.2	91	1/22/99	9.2	7,191			
			8/3/98	0.2	90						
			8/13/98	0.7	88						
			8/19/98	0.4	82						
			9/17/98	0.3	72						
			10/16/98	0.4	50						
			11/11/98	0.6	51						
			12/15/98	0.7	47						
			1/19/99	0.8	59						

Table 7: Results of groundwater sampling – Wells SSM-006 and SSM-007

SSM-006 B			SSM-006 C			SSM-007 B			SSM-007 C		
	D.O.	TCE		D.O.	TCE		D.O.	TCE		D.O.	TCE
Date	mg/L	ppb	Date	mg/L	ppb	Date	mg/L	ppb	Date	mg/L	ppb
7/21/97	8.1	740	7/22/97	3.1	179	7/21/97	6.2	237	7/21/97	4.6	1,671
8/22/97	7.7	671	8/21/97	5.5	1,428	8/19/97	8.2	173	8/19/97	5.8	1,935
8/27/97	9.6	744	8/27/97	6.3	1,259	8/27/97	9.7	224	8/27/97	7.1	1,550
10/8/97	8.2	599	10/8/97	7.1	991	10/8/97	8.9	218	10/8/97	6.5	1,209
11/5/97	9.0	597	11/5/97	7.3	419	11/4/97	9.0	182	11/4/97	6.7	1,371
11/20/97	9.1	495	11/20/97	7.9	462	11/19/97	9.4	185	11/19/97	7.3	1,670
12/11/97	9.4	1,162	12/11/97	7.4	318	12/10/97	9.2	190	12/10/97	7.4	1,541
1/14/98	8.8	409	1/14/98	8.8	1,012	1/14/98	9.0	195	1/14/98	7.4	1,512
2/10/98	8.4	406	2/12/98	9.4	1,280	2/12/98	9.1	252	2/12/98	7.3	1,308
3/3/98	9.2	465	3/3/98	10.0	1,256	3/4/98	9.3	335	3/4/98	7.4	1,318
3/19/98	8.9	428	3/19/98	9.1	1,403	4/2/98	8.9	260	4/2/98	6.6	924
3/31/98	9.8	414	4/2/98	9.2	1,269	4/16/98		204	4/16/98		777
4/15/98	9.3	504	4/16/98	9.8	1,291	5/13/98	9.9	285	5/13/98	7.4	779
5/13/98	10.0	271	5/13/98	10.1	1,276	6/12/98	8.2	100	6/12/98	7.0	509
6/12/98	8.2	340	6/12/98	8.5	1,113	7/23/98	8.3	132	7/22/98	6.9	491
7/23/98	8.6	394	7/23/98	9.6	1,529	8/25/98	9.2	79	8/25/98	7.2	420
8/25/98	9.0	363	8/25/98	9.9	877	9/18/98	9.3	74	9/18/98	7.1	598
9/18/98	8.9	748	9/18/98	9.9	843	10/16/98	9.6	103	10/16/98	7.8	1,050
10/19/98	9.4	895	10/19/98	9.2	729	11/11/98	9.3	129	11/11/98	8.0	2,849
11/13/98	9.1	761	11/13/98	8.6	1,406	12/15/98	9.9	214	12/15/98	8.9	2,409
12/16/98	0.0	1,057	12/16/98	0.0	1,926	1/21/99	9.3	215	1/21/99	8.0	2,179
1/21/99	9.0	1,233	1/21/99	9.0	2,904						

Table 8: Results of groundwater sampling – Wells SSM-008 and SSM-009

SSM-008 B			SSM-008 C			SSM-009 B			SSM-009 C		
	D.O.	TCE		D.O.	TCE		D.O.	TCE		D.O.	TCE
Date	mg/l	ppb	Date	mg/l	ppb	Date	mg/l	ppb	Date	mg/l	ppb
2/13/98	4.1		2/13/98	0.5	1,085	1/15/98	4.8	7,613	1/15/98	3.2	1,259
3/5/98	1.2	7,909	3/5/98	3.2	1,044	2/13/98	3.1	4,564	2/13/98	3.7	1,187
4/2/98	0.9	6,233	4/2/98	2.5	1,130	3/5/98	2.6	2,673	3/5/98	4.8	1,272
4/17/98	1.8	5,312	4/17/98	4.6	1,021	4/2/98	2.6	1,842	4/2/98	6.4	1,308
5/14/98	1.9	4,328	5/14/98	4.8	1,153	4/17/98	3.7	1,670	4/17/98	6.3	1,274
6/15/98	3.3		6/15/98	6.8	1,133	5/14/98	4.2	2,140	5/14/98	6.2	1,589
7/24/98	2.8	3,372	7/24/98	5.3	1,900	6/15/98	5.4	1,109	6/15/98	8.5	1,310
8/26/98	3.2	1,608	8/26/98	4.7	1,122	7/23/98	3.8	2,012	7/24/98	8.1	1,760
9/29/98	3.8	3,742	9/28/98	4.1	1,009	8/26/98	1.9	1,129	8/26/98	7.8	1,021
10/19/98	3.2	8,252	10/19/98	4.0	1,147	9/28/98	1.3	981	9/28/98	6.6	966
11/16/98	3.2	14,864	11/16/98	3.9	1,635	10/19/98	2.4	1,193	10/19/98	7.4	1,128
12/16/98	0.0	10,309	12/16/98	0.0	1,256	11/16/98	3.2	3,249	11/16/98	7.1	1,460
1/22/99	3.9	12,950	1/22/99	4.1	1,753	12/16/98	0.0	3,534	12/16/98	0.0	1,436
						1/22/99	3.3	5,781	1/22/99	7.5	1,747

Table 9: Results of exhaust air sampling – SSR-012

Period	Inlet airflow (cfm)	Exhaust air conc. (ppmv TCE)	Exhaust air conc. (ppmv PCE)	Cumulative lbs. TCE removed	Cumulative lbs. PCE removed	Notes
Jan-97	18	1.7	0.007	0.3	0.001	
Feb-97	22	1.7	0.007	1.0	0.006	
Mar-97	30	1.2	0.024	1.9	0.020	
Apr-97	30	1.2	0.024	7.3	0.052	
May-97	30	55	0.400	46.2	0.265	1
Jun-97	30	56	0.400	76.8	0.517	
Jul-97	28	75	1.500	122.5	1.276	
Aug-97	33	81	0.670	182.7	1.690	
Sep-97	26	55	0.150	214.6	1.783	2
Oct-97	38	50	0.450	255.6	2.067	
Nov-97	38	52	0.540	303.8	2.537	
Dec-97	36	78	0.950	336.8	2.871	3
Jan-98	35	78	0.950	100.9	3.497	
Feb-98	33	76	1.100	454.0	4.129	
Mar-98	33	72	0.730	508.0	4.582	
Apr-98	33	64	0.650	554.2	4.973	
May-98	33	62	0.054	600.0	5.282	
Jun-98	33	63	0.930	643.5	5.840	
Jul-98	33	54	1.150	679.7	6.551	
Aug-98	31	67	2.220	729.2	7.840	
Sep-98	0	NA	NA	729.2	7.840	4
Oct-98	0	NA	NA	729.2	7.840	
Nov-98	0	NA	NA	729.2	7.840	
Dec-98	0	NA	NA	729.2	7.840	

Notes: 1) Well was redeveloped 4/24/97. Air injection submergence = 50.6 feet.
2) Air injection submergence reduced to 30.6 feet.
3) Air injection submergence returned to 50.6 feet.
4) Well removed from service for upgrades.